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INSULATED ELECTRIC CABLES
MATERIALS AND DESIGN

INSULATED ELECTRIC CABLES

I. MATERIALS AND DESIGN

II. MANUFACTURE AND INSTALLATION

INSULATED ELECTRIC CABLES

IN TWO PARTS

I. MATERIALS AND DESIGN

BY C. J. BEAVER, M.I.E.E.

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PREFACE

ALTHOUGH there has been no scarcity, during the past few years, of papers and articles relating to insulated cables, many of them representing results of valuable research by brilliant workers, they have been almost invariably devoted to electrical aspects of the subject.

It needs little consideration to see that a proper perspective of the whole field is essential to the effective application of the knowledge rendered available by such research. Obviously, its value can only be adequately appraised in conjunction with knowledge of other factors on which electrical properties are dependent, and to which they are closely related.

The general principles underlying the design and manufacture of cables, and bearing upon their efficient utilisation and maintenance, do not appear to have been comprehensively dealt with in any work so far published.

My first endeavour, therefore, in writing this book, has been to supplement, balance, and focus the existing knowledge of the subject, in the earnest hope that the views expressed—which, if they have no other merit, are at least based upon many years' experience—may tend to conserve, and even, to some extent, guide the efforts of future workers.

It will be only too apparent that in the present state of our knowledge, and at this stage of our progress towards the ideal cable, we get hardly more than occasional glimpses of the interdependent relations of the various chemical, physical, and electrical components in the whole field, and only a shadowy insight into means of drawing them closer together; but one cannot help feeling that the dawn of a period is approaching when, by the proper application of our advancing knowledge of chemistry, physics, and ionic theory, we shall be able to crystallise into a harmonious structure many things which are only, at present, dimly within our ken.

Of necessity, the wide ground traversed in this book has entailed the making of various statements and suggestions for the first time; but, in consonance with the broad view referred to above, I have taken care, when dealing with suggestive points, not to press them further than the weight of evidence bearing thereon would appear to justify. If I have erred in this direction, it is because I am keenly alive to the fact that the cable industry is in a critical stage of its technical progress, and is consequently susceptible to incalculable harm from immature suggestions, insufficiently proved theories, and deductions which are not completely justified by the results of tests from all angles.

A further object I have had in view is the promotion of a wider knowledge among cable-users of the properties of cables, and a better appreciation of the reasons which govern the various forms of construction and which determine the most suitable types for given duties; so that in the rapidly expanding fields of utilisation of electric power, consulting engineers and the designers and users of plant and apparatus, may not only have closer ideas regarding working relations between the important adjunct constituted by the supply cables and the generating, transforming, or consuming devices, but also fuller knowledge regarding accom-

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modation and protection of the cable, necessitated by the particular kind and degree of vulnerability of the type of cable chosen for a given set of conditions.

It is not in the best interests of the electrical industry that the cable manufacturing section of it should be regarded as a watertight compartment, although, having little in common with any other branch, it must always be a more or less specialised section. Co-operation and mutual understanding between maker and user regarding requirements is highly desirable in the interests of technical and commercial efficiency.

Although not originally intended, a number of circumstances combined to indicate the advisability of dividing this work into two volumes. The scheme of treatment of the subject lent itself quite naturally to this, and so the present volume deals with materials, and fundamental principles bearing on questions of design, while the second volume will be devoted to matters regarding manufacture, testing, installation, usage conditions, maintenance, current rating, causes of deterioration, etc.

My sincere thanks are due to Messrs H. M. Crellin, A.M.I.E.E., T. J. Fairfield, A.M.I.E.E., E. L. Davey, B.Sc.(Eng.), and N. Dixon, A.M.C.T., A.I.C., for assistance in many ways. Mr N. Dixon imposed upon himself the task of reading all the proofs and compiling indexes, etc., for which help I am particularly grateful.

I also wish to express my thanks to Messrs W. T. Glover & Co., Ltd., for kind permission to publish some of the information contained in this book.

CHARLES J. BEAVER

TRAFFORD PARK
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I. INTRODUCTORY

CHAPTER I

DEVELOPMENT OF ELECTRIC CABLES

The Electrical Engineering industry in its inception had the advantage over many of the older industries in that it was based on a foundation of comparatively modern scientific discovery.

The cable manufacturing branch of the industry, however, has not shared the effects of the advantages to the same degree as, for instance, the dynamo and motor manufacturing branch.

There are probably two or three general but more or less tangible reasons for this. In the first place cable manufacture is a peculiarly distinct branch. Its products and methods of production have little in common with any other branch; its requirements differ because of the preponderating necessity for and importance of continuous and self-contained insulation, and the conditions of duty of the finished goods demand a wider variety of special materials than in other branches.

Consequently more physical, chemical, and other fundamental scientific problems—and these of very diverse character—are entailed. Yet for reasons connected with the conditions under which manufacturing operations began, viz., chiefly by adaptation of existing—often non-electrical—industries, the comparative unattractiveness of cable manufacture to scientifically trained engineers, the complexity, obscurity, and wide variation of requirements for different purposes, and so on, these problems have not been attacked with the same vigour and efficiency as the problems of some other branches of electrical engineering.

Although the present work is intended to deal almost exclusively with present-day practice in the manufacture and installation of electric cables, it will be useful to briefly review the development of the insulated cable over the past thirty to forty years in order that the present conditions may be the more intelligently focused and the essentials logically noted.

Prior to the above mentioned period the gutta percha insulated submarine telegraph cable had been brought to a high state of perfection, but as is well known gutta percha is physically and chemically unsuitable for the insulation of cables to be used at even slightly elevated temperatures or when exposed to air. Considerable quantities have been used in the past on land for telegraph and signalling purposes (chiefly on railways, etc.), but the necessary exclusion from air has been provided for by laying the wires in compound filled troughs, and of course no appreciable heating occurs in working.

In the early days of electric lighting, various systems were introduced in this country and in America which virtually amounted to bare conductors laid in pipes or ducts filled with oil or compound, the conductors usually having wrappings which were practically nothing more than spacing materials. The earliest notable instance of this kind was the Edison system, which was somewhat largely used in the United States. In this system the conductors consisted of copper rods wound over with jute rope and drawn into iron pipes in lengths up to about twenty-five feet, the

pipes being subsequently filled with bituminous compound, special joint-boxes being used to joint both the pipes and the conductors at these intervals and to act as tee-boxes for services when required.

Another system, of which examples have been seen in this country, was that designed by David Brooks in the early eighties. In this system an iron pipe line was first laid and comparatively long lengths of conductor—lapped with jute, and oil impregnated—were drawn in, the pipe and joint-boxes being kept full of oil under pressure.

The Brooks system was tried in the United States, and was subsequently improved and used by Messrs Johnson & Phillips in this country.

Another bare-conductor system used by the Interior Conduit Co. of America consisted of impregnated paper tubes jointed with paper ferrules and laid on timber in a trench, surrounded by bituminous compound, bare-stranded conductors being subsequently drawn in.

The Crompton system of bare-strip conductors strained up between insulators in a culvert, was extensively used in this country, and some of it is in use to-day after thirty years' service.

In effect it is an adaptation of the principles of overhead construction to underground work, and so far as freedom from breakdown is concerned has been remarkably successful. The author has seen it stand up to conditions of short circuit on the system which caused the conductors to " whip " towards each other by electromagnetic attraction, to conditions of load which made the conductors perceptibly sag, and to complete flooding with sewage, without failure. Slow or intermittent leakage, however, has been known to cause formation of metallic sodium at an insulator, which has been suspected of causing an explosion by being acted on by water, the resultant flame igniting the coal gas which is usually present in culverts in large towns.

Other bare-conductor systems have been based on the solid system of laying, the conductors being laid on insulating bridges such as glass in troughs filled with bituminous compound. Many such systems, varying chiefly in details of the troughing, filling compound, and bridge or spacer materials, have been introduced and tried during the past twenty to thirty years, without permanent success.

In order to test the general possibilities of such systems, the author made some exhaustive practical tests and comparisons extending over a period of four or five years, commencing in 1902.

These tests were made on long service lines on a certain power-supply system, and were based on a construction which, from the insulation standpoint, was perhaps the most favourable—within commercial limits—for the purpose, viz., asphalt trough.

The comparisons embraced two lines of possible design. Firstly, bare conductors laid on asphalt bridges in the asphalt trough. In this case extraordinary precautions were taken under the author's supervision to ensure perfect jointing of the lengths of troughing and homogeneity of the bitumen filling. In addition, perfect weather conditions were chosen for the construction of the line. Although

the working pressure in this case was only 500 volts, no sign of weakness was discoverable after testing at 25,000 volts, and the insulation resistance of the complete service—which was over 50 yards in length—was approximately 250 megohms per mile.

The idea of the second line of design was to divide the burden of requirements as it were between the cable-maker and the manufacturer and installer of the troughing. In this case the conductor was insulated to an extent which was sufficient to withstand the factory tests, including twenty-four hours' immersion in water and the subsequent electrical pressure and insulation resistance tests, but not sufficiently to withstand rough handling or prolonged exposure to underground conditions. In other words, the cable was designed to be sound until after it was laid, and thereafter the system of laying was to take the responsibility of maintaining its soundness. The laying, under this branch of the experiments, was undertaken by the makers of the troughing, and the weather, soil, and other conditions could not be chosen as in the bare conductor case, the lines being laid in the ordinary course of power-supply business.

Two variations under this second heading were tried. In one case the cables were L.T. single-core, and in the other 3000-volt 3-core. The conductors were in both cases insulated with impregnated paper, and sheathed with a thin layer of bitumen sufficient for the purposes above described.

Briefly, the result of the comparisons was as follows :—

The 3-core 3000-volt cable failed within two to three months. The failure was found to be fairly widespread and was clearly due to ingress of water. (In this case the ground in which the cable was laid was practically waterlogged.)

The single-core L.T. cable failed from the same cause in about nine months.

The bare-conductor L.T. line only developed one fault in five years, this being at the joint between the end of the line and its disconnecting box. Its insulation resistance, however, gradually deteriorated, indicating slow ingress of moisture, and it was replaced by insulated cable after six years. It has to be borne in mind, however, that the laying conditions in this case were considerably better than average, and the results should be discounted correspondingly.

The conclusion which must obviously be drawn from all the foregoing instances in which laying construction has been attempted to be substituted for cable-manufacturing operations, is that they fail from one or more of the following causes :—

(*a*) Mechanical inefficiency of construction.
(*b*) Electrical inefficiency of the mechanical construction.
(*c*) Inefficacy of bituminous or similar compound fillings to prevent ingress of moisture, due to the impossibility of obtaining perfect homogeneity therein under practical conditions of laying.
(*d*) High initial cost and bad space factor.

It clearly follows that for the efficient fulfilment of the technical, commercial, and practical requirements of underground transmission or distribution the insulation of cables should be entirely dependent on the construction in the cable factory,

and their mechanical protection either entirely or partially so dependent on the conditions and method of installation.

Turning now to the case of the insulated cable and the causes of its early troubles, it has to be borne in mind that in the very earliest days of electric lighting—the first instance of the necessity for appreciable voltages—previous experience of anything approaching efficient insulation was confined to the submarine cable-makers, and, as previously mentioned, the dielectric material with which they had become familiar—gutta percha—was of limited use for the purpose.

For a period, and under certain favourable conditions, wire insulated with silk or cotton lappings treated with varnish or wax compounds was satisfactorily used, and later, lappings of pure rubber were combined with cotton lappings and braidings and treatment of the latter with wax or ozokerite.

Even this combination, however, was soon found inadequate, and the adoption of the vulcanised rubber type of insulation, originated by Hooper in 1860, became general. It is interesting to note that this type of insulation, although based, so far as can be judged from published descriptions of its inception, on erroneous suppositions, is still in general form the standard type in this country.

From the point of view of comparatively efficient manufacture, the vulcanised rubber type of dielectric, being non-hygroscopic, gave the advantage that it could be tested in water over a sufficient period to cause faults to declare themselves, thus, in a limited degree, tending to approach the efficiency of the submarine gutta-percha cable from this aspect. Nevertheless, faults in manufacture were so frequent that for many years fault location and repair work formed a regular part of the manufacturing processes prior to the arrival of the cable at the test tanks, instead of constituting—as now—emergency processes.*

This comparatively low standard of manufacture was often reflected in the behaviour of the cable in use when the conditions were sufficiently severe. It must be remembered, however, that the knowledge and manufacturing facilities of the maker were also in early stages of evolution.

If the conditions of the present time, when wire mills, rubber-works, and even more remote factors are included in the equipment of the cable manufacturer, and his technical control is on a much higher level, are contrasted with his lack of such facilities in the period referred to, the earlier failures are certainly not surprising.

There were, on the other hand, some incidental factors which were favourable. Competition had not cut down quality, and comparatively high grades of rubber compound were used. Thicknesses of dielectric provided a good margin of safety on H.T. cables for the maximum pressure then in vogue, *i.e.* 2000 volts ; and single-phase A.C. requirements caused the concentric type of cable—in which the inner insulation is incidentally well protected from air and moisture by the outer—to be largely used. A large quantity of cable of this type is in use at the present time after more than a quarter of a century's service.

In the case of L.T. rubber cables used as underground mains, the chemical

* Under modern conditions of manufacture the average percentage of faulty lengths in a large daily output should not exceed 1 to 2 per cent.

protection and—to some extent—electrical reinforcement of the " solid " method of laying was helpful, but on the whole the general results led to the permanency of rubber insulation being impugned, and its high cost led to efforts being made to develop other materials.

The most notable efforts in this direction so far as this country was concerned resulted in the introduction by Messrs Callender of vulcanised bitumen insulation, and in America of " Kerite," " Okonite," and a number of other ingeniously compounded cable insulating materials designed to obviate the technical and commercial disadvantages of " straight " vulcanised rubber compounds, these substituted materials consisting, according to Dr F. A. C. Perrine,* of materials containing " oxidised oils, special varieties of rubber shoddy, petroleum residuum, ozokerite and special grades of bitumen mixed with rubber and subsequently vulcanised."

Some of these American products have given excellent service, showing great resistance to atmospheric and other adverse influences, but they have usually been employed in appreciably greater thicknesses than are used in this country, and this factor alone is greatly in favour of permanence, apart from the intrinsic properties of the materials.

During the past two or three years there has been a recrudescence or repetition of history in this country in the matter of " ites," † and almost every firm of cable manufacturers has in its armoury some special form of insulation bearing some general, even though only superficial, resemblance to the American types above mentioned. Their *raison d'être* is that their properties are generally such that they can be usefully employed to bridge gaps in various directions between the spheres of usefulness already filled by standardised types of cable. For example, in some circumstances in which vulcanised bitumen would ordinarily be used, but where unusually severe demands are made upon its mechanical properties—such as pulling out and reinstalling in colliery roadways—and where, therefore, the properties of rubber are really demanded, the use of one of these materials may fulfil the requirements admirably. Again, under conditions which entail a maximum of physical properties, but comparatively little in the way of electrical requirements—for example, railway signalling work—a rubber type of dielectric in substantial thickness is indicated, although a high tension rubber cable is not required. In point of fact, the demand from some of the Colonies (notably Australia) for " Kerite " cable for the latter class of work, was a potent factor in fostering the growth of the " ite " type of cable in this country. British railway engineers are becoming large users for their very exacting work on signalling systems.

With regard to vulcanised bitumen, which was the principal if not the only material which directly and to a serious extent replaced vulcanised rubber insulation for underground mains, Sir John Snell in his book on *The Distribution of Electrical Energy*, p. 194, says that " earlier cables were insulated with pure bitumen, but a practical difficulty arose from the repeated decentralisation of the cores. Callender's

* F. A. C. Perrine, *Conductors for Electrical Distribution*, p. 106, 1903.

† " Gloverite," " Maconite," " Bidurite," " Permanite," etc., are well-known instances. Dr Perrine's statement, quoted above, referred to American products.

now adopt a substance produced from the distillation of certain oils which is sulphurised. . . ."

These vulcanised bitumen cables which have been largely used up to the present time—chiefly for L.T. distribution work in towns and cities—are usually laid on the solid system which is admirably suited to the requirements of this type of insulation, both from the mechanical and electrical reinforcement standpoints.

In addition to the unavoidable inefficiencies of cable insulation in the early days due to the more or less primitive state of the art, a powerful factor in early cable troubles was inappreciation of the necessity of close maintenance tests and the consequent lack of provision of facilities for carrying them out.

Even where the necessary provisions were made the results of tests were rendered more or less futile, as the general method of underground installation militated against the results of tests truly representing the electrical state of the cable dielectric.

In non-metallic sheathed cables an insulation resistance test would include values due to the surrounding media, which in the case of cables laid on the solid system would be considerable. Further, there would always be, in the case of solid laid cables of this type, a liability for a partially developed fault to be sealed up by the melting of the trough-filling bitumen; and in any case fault location by electrical tests would be very difficult.

When lead covered cables—insulated with impregnated cotton and jute—came into vogue, the facilities were automatically improved by the fact that the lead covering constituted an " earth " boundary to the cable dielectric proper, but in the light of more mature experience, it is clear that the importance of efficient maintenance tests was not, in those early days, sufficiently realised. (In the author's opinion it is not fully appreciated even at the present time.) Lack of experience and of scientific investigation also militated against correct diagnosis of troubles and consequently against the provision of curative or preventive remedies.

Even after the use of lead sheathed cables became very general, a number of years elapsed before the necessity was fully realised of bonding the lead sheaths continuously, and suitably cross bonding and earthing them. For a long time, indeed, there were advocates of the reverse procedure, *i.e.*, keeping sections of lead sheath isolated from one another. Some even went so far as to propose joint boxes made of insulating material, in order to ensure such segregation of sheathing metal.

This, of course, tended to nullify the tendency above referred to for lead sheaths to make maintenance tests more efficient.

The disastrous effects experienced a few years later, on more than one deteriorated network—whereby a fault in one part caused arcing from lead to earth at many other parts—clearly indicated the necessity for bonding and earthing metal sheaths; the lesson was more or less quickly learned and the principle of bonding and earthing more or less efficiently carried out.

Prior to 1890 lead sheathed cables, other than rubber insulated cables, had been mostly insulated with impregnated jute or cotton yarns, but about that time

Ferranti used paper impregnated with waxy compounds in the construction of his world-famous concentric mains which were used in connection with his scheme for transmitting power (single phase current at 10,000 volts) from Deptford to London.

As is well known these mains consisted of copper tubes arranged concentrically, the inner one being covered to the required thickness by winding on the strips or sheaths of impregnated paper under the pressure of rollers, and then pushed into the outer tube, which was drawn down to closely fit the underlying "inner" dielectric. The outer tube was similarly insulated, and the whole was slipped into a wrought-iron tube, compound being subsequently forced into the clearance space.*

Although this construction has been considered as the nearest approach, before or since, to orthodox engineering practice, it suffered from the tremendous disadvantage of frequent joints, because its rigidity precluded a greater length than about twenty feet.

About the same time paper insulated cables of the ordinary type (with stranded conductors) sheathed with lead were being produced in America, and the British Insulated Wire Company, formed by Ferranti and others, was established at Prescot, Lancashire, for the manufacture of this type of cable.

In subsequent years it was taken up by all the large cable manufacturers, and has gradually displaced other fibrous insulated cables, although impregnated jute cables are still made, to a very limited extent, in both lead sheathed and bitumen sheathed types, and are standardised by the B.E.S.A. on a basis of equality (as regards radial thickness) with impregnated paper for low tension work.

The improvement of laying and jointing practice followed, due to various factors in the general state of development of lighting and power supply and of cable-making progress.

Extensions to existing networks frequently necessitated additional feeders to outlying districts, and these were—for reasons of economy—usually of the paper lead-covered and armoured type laid direct in the ground.

The development of electric tramways and power supply systems required new feeder and distributor systems, and the paper lead-covered type of cable was used more and more for these purposes.

Cable-making firms took up the manufacture and supply of joint-boxes, feeder pillars and other accessories, realising from their experience that a great deal of the early troubles were due to defective conditions of installation. Parenthetically, it may appear strange that the cable-makers had not to any great extent taken this logical attitude at a much earlier stage of development; that they had not done so was due to the fact that the requirements were not recognised to a sufficient degree.

The situation, so far as its bearing on maintenance was concerned, was therefore gradually improved by reason of the use of metallically sheathed cables and the fact that the cable accessories tended to come into the hands of the makers of the cables,

* Patent No. 16, 237/1889.

who were naturally interested in their upkeep, and would therefore pay due attention to provisions for sealing, bonding, etc.

Although, however, this resulted in better facilities for maintenance and fault location, the effective and systematic use of such facilities often left much to be desired.

So far as the paper lead-covered type of cable itself was concerned, it had the advantage over rubber of freedom from deterioration with age, because—given proper materials and manufacturing treatment—the chemical stability of impregnated paper is very great.

Even the hygroscopic character of the paper dielectric, which is usually regarded as a disadvantage, is perhaps not entirely so when considered from the broadest aspect, because its very susceptibility to moisture necessitates efficient sheathing and effective sealing of joints, end connections, etc., and it therefore escapes certain troubles which sometimes arise in non-hygroscopic types, due to trims being insufficiently protected from moisture.

Under proper conditions of installation, therefore, the disadvantage of hygroscopicity is only of considerable moment in cases of imperfection of, or damage to the lead sheath resulting in ingress of water.

The chemical stability of the lead covering is also very great, provided due precautions are taken to prevent extraneous actions, of which by far the most harmful, and at the same time the most insidious, is electrolytic corrosion. It may here be noted that the principal sources of electrolytic action are either leakage current from the cable itself (*e.g.*, from inefficiently sealed joints or end connections, or from faults in course of development) or from some other circuit, in the leakage path of which the lead sheath offers a convenient conducting route.

Clearly, therefore, the worst enemies of this type of cable may be defeated by the use of proper fittings and accessories and by well-designed bonding arrangements which prevent such differences of potential between the lead sheath and its surroundings as may lead to electrolytic corrosion.

The intrinsic merits and the technical and commercial advantages of the paper lead-covered cable have therefore been enhanced and protected by the foregoing incidental factors connected with its installation and maintenance, with the result that it is at the present time the most important type of cable for electrical transmission and distribution ; and from the aspect of scope—over the range of sizes and forms of cable required, and the manifold conditions of service encountered in practice—may be regarded as the foremost of the surviving types of insulated cable.

With the advancing demand for cheap electrical power for industrial purposes, and the equally rapid development of large and efficient units of plant resulting in reasonably low generating costs, the design of " super " power stations and schemes for linking up the areas of existing supply authorities received considerable attention in the second decade of the present century, though progress was seriously hindered by the Great War.

Naturally, a demand for cheap transmission costs was a corollary to these advances, and the cable-maker was called upon to produce cable suitable for three-phase transmission at working pressures of 30 K.V. and upwards, which entailed further development of the paper-insulated lead sheathed type.

A fair amount of experience of 20 K.V. operation was already available, notably on the North-East Coast; but the economic aspect of the new demand entailed something more than a simple expansion of the 20 K.V. cable. It necessitated appreciable increase in dielectric stresses in order to keep down the thickness of dielectric—and in turn the diameter and weight of the cable—within practicable limits.

At the same time, the minimising of dielectric losses became a matter of paramount importance, to which even dielectric strength was secondary, and this raised questions of material as well as of assembly of the component parts of the cable. The question of the exclusion of air and gases from the dielectric—to some extent related to that of dielectric loss—came decisively into the foreground, because stress values at which they became ionised had to be appreciably exceeded.

In short, the more exacting conditions demanded drastic revision of manufacturing methods in order that the product should be put on the higher plane necessitated by the above noted factors in the case.

Similarly, matters of both principle and detail in connection with the jointing of these " super-tension " cables called for revision and improvement; they proved to contain even more pitfalls than the manufacture of the cable, owing partly to the complexity of the combined physical and electrical problems involved, and partly to the inherent differences between results obtainable in the field as compared with those producible in the factory.

Appreciation of these points was not universal, but differed in degree in various quarters, and a good deal has been learned from both experience and research since the early days of super-tension work. It is interesting to note, however, that refinements and modifications of procedure and manufacture rather than of materials have been involved in overcoming the difficulties, and the intrinsic merits of the paper-insulated, lead sheathed type of cable have not been impugned.

For practical purposes the other surviving types at the present time may be taken as vulcanised rubber, vulcanised bitumen, and varnished cambric, and each of these has a wide field of utility.

For instance, vulcanised rubber is particularly suited to interior uses, from lighting wires to heavy connecting cables for motors, transformers, and other apparatus at working pressures up to about 10,000 volts. Its principal advantages are high electrical and mechanical strength and waterproofness, and its limitations chiefly relate to cost, and, at high pressures, its susceptibility to the action of ozone formed in its vicinity by brush discharge effects.

Vulcanised bitumen, while retaining to a considerable extent its hold on underground distribution work at low pressures (feeders nowadays being usually E.H.T. cables of the paper lead-covered type), has also found, by reason of the peculiar and almost unique conditions involved, a great vogue in colliery and similar work at

pressures up to about 6000 volts, the maximum pressure at the present time for feeders conveying current to the pit bottom.

The conditions referred to are chiefly great liability to damage in conjunction with wet surroundings, and the principal advantage of vulcanised bitumen is that faults developed under this combination of risks remain local, instead of affecting a long length, as they are liable to do in a cable having hygroscopic insulation and fixed in a vertical position—the latter being the usual condition in a shaft cable. The chief limitations of this type are of a physical or mechanical character, and although these disadvantages are helped out by design and manufacture to a considerable degree, they have to be recognised in installation practice to some extent.

The Varnished Cambric type of cable, though largely used in connection with machine and transformer cabling and other similar work, has not found much favour in this country for lighting and power distribution purposes. There are several reasons which combine to account for this, and although the matter is referred to elsewhere in this work, it may be desirable from the point of view of this chapter to briefly refer to them.

The varnished cambric of commerce is not specially produced for cable-making purposes, and complete expulsion of moisture is not attained as in the case of the fibrous dielectric materials prepared by the cable-maker. As the normal or residual moisture is enclosed by the superficial varnish films, special treatment is required to expel it, in order to make the material comply with the essentials of a fibrous dielectric.

As regards hygroscopicity, varnished cambric occupies an intermediate position between impregnated paper and rubber or vulcanised bitumen, because access of moisture to its fibrous (and therefore hygroscopic) foundation is retarded by the surface films of varnish and by the partial filling of the interstices between the warp and weft.

Early experience in America showed that the resistance to moisture of varnished cambric used as cable insulation is not sufficiently good to prevent trouble arising in course of time in cables used under average underground conditions, and present American practice is to lead-cover or bitumen-sheathe cables used as underground feeders or distributors. In effect, therefore, it will be seen that varnished cambric is little more than a substitute for impregnated paper so far as ordinary underground cable work is concerned. At the same time, any advantages it possesses as regards mechanical strength and resistance to moisture do not, under these circumstances, come into operation to a sufficient extent to justify the extra cost, nor do its electrical properties allow a reduction of dielectric thickness which would counterbalance this economical aspect in high-tension cables, where the cost of insulation is a predominating factor in the total cost of the cable.

While as a substitute for paper it would doubtless be acceptable under I.E.E., British Fire Office, and other Rules, the necessity for standardising it in any way in this country does not appear to have arisen, probably because of the above-mentioned economical aspect.

There is, however, a considerable field of useful application for this type of insulation apart from ordinary wiring and underground cable requirements.

If, for example, its initial preparation could be so improved or supplemented as to make it free from moisture before application to the cable, and further, if in course of application and mechanical protection (by compounded braidings) its moisture-resisting properties could be sufficiently enhanced, there should be a wide sphere of usefulness for it in situations where it would be required to resist atmospheric moisture alone, *e.g.*, in power and sub-station cabling, motor, transformer, and switchgear connections, etc.

Enormous amounts of cable are used for work of this kind under conditions which as regards deteriorating effect are closely circumscribed, and subject to close observation. These conditions, it must be noted, do not apply to ordinary underground cable work, where absolute protection against water and other possible inimical influences must be provided for without differentiating between the various degrees to which such influences may operate from place to place.

In general, the moisture-resisting qualities of the varnished cambric type of cable may be made sufficiently good, when reinforced by special compounded braidings, etc., to withstand the working conditions of selected situations.

Again, there are many situations where the moisture conditions may be such that a waterproof sheath is required, but lead covering is undesirable on account of weight (*e.g.*, in a mine shaft) or on account of bulky and expensive end-boxes, as in connections between apparatus and switchboard, etc.

In such cases the use of vulcanised bitumen-sheathed, varnished cambric insulated cable will often be found to fulfil the requirements with regard to resistance to moisture and other deteriorating influences. It may, further, on account of the mechanical excellence of the varnished cambric lappings—a property which, as noted above, is to a great extent wasted in the case of ordinary underground varnished cambric cables—be used for semi-portable work in connection with mining, quarrying, dredging, and constructional work. For these latter purposes, of course, tough vulcanised rubber would be more satisfactory as a sheathing material than vulcanised bitumen, but unfortunately varnished cambric is not amenable to the requisite temperature conditions of vulcanisation.

Enough has been said, however, to indicate that there is a wide scope for the varnished cambric type of insulated cable, provided it is brought into line (as regards insulating qualities, and moisture, etc., resisting properties) with the requirements of cable-making practice.

From the foregoing it will be seen that the evolution of the insulated cable has resulted in placing at the disposal of the cable-maker at the present time four general types of insulation, viz., paper, vulcanised rubber, vulcanised bitumen, and varnished cambric, and that the majority of working conditions under which insulated cables are required to operate may be economically met by these types or a judicious combination of them.

There is very considerable room for improvement in all of them, not only in the composition, form, and properties of materials, and methods of their application

and protection, but also with regard to conditions of installation and maintenance of the finished cables. Moreover, the burden of such improvement must be shared between the designer and the user, if the evolution curve is to become steeper in accordance with the sharply accentuated requirements of the future regarding cheap power transmission and distribution.

In other words, the general outlook in connection with the development of insulated cables should be such that research relating to production is not hampered by inflexibility of practice on the part of the user.

II. MATERIALS

CHAPTER II

MATERIALS USED IN THE MANUFACTURE OF CABLES

INTRODUCTORY

The manner of the development of the cable-making industry, *i.e.* branching from other industries, necessitated the purchasing by the cable-maker of some of the components of his finished product in a comparatively advanced stage of manufacture. For instance, if he were not already a rubber manufacturer, he would usually buy his pure and vulcanising rubbers from established rubber-works. Again, unless he came into cable manufacture from the wire industry, he had to obtain his conductor material in the form of wire, tinned or " plain " according to the type of dielectric with which it was to be insulated. Some came in from industries unconnected with either wire or rubber manufacture, and therefore had to purchase each of these fundamental components from outside sources. As one who had to struggle against adverse circumstances of this kind in the early days, the author can testify to the difficulties involved.

With regard to conductors there was comparatively little to complain of with regard to the drawing and annealing of the wire or the conductivity of the metal, although accuracy was a long way below the present-day level, but the important matter of tinning the wire was by no means satisfactory.

On the one hand the cable-maker had no very accurate idea of the functions of the tin coating—even at the present time erroneous statements on this point are frequently published—nor of the important bearing of its perfection on the durability of the rubber dielectric in contact with it, and consequently could lay down no standard of quality for the wire mill to work to. On the other hand, there was no generally accepted method of preparation of the wire, no control of temperature, and little appreciation of the importance of cleanliness, in fact, everything was done by " rule of thumb."

With regard to rubber, the cable-maker simply specified his " mixings " to the rubber manufacturer and took his chance of the strict, and at the same time intelligent interpretation and fulfilment of his specifications by the latter. The difficulties in the way of obtaining perfect or even reasonably good results under these circumstances were obviously very great.

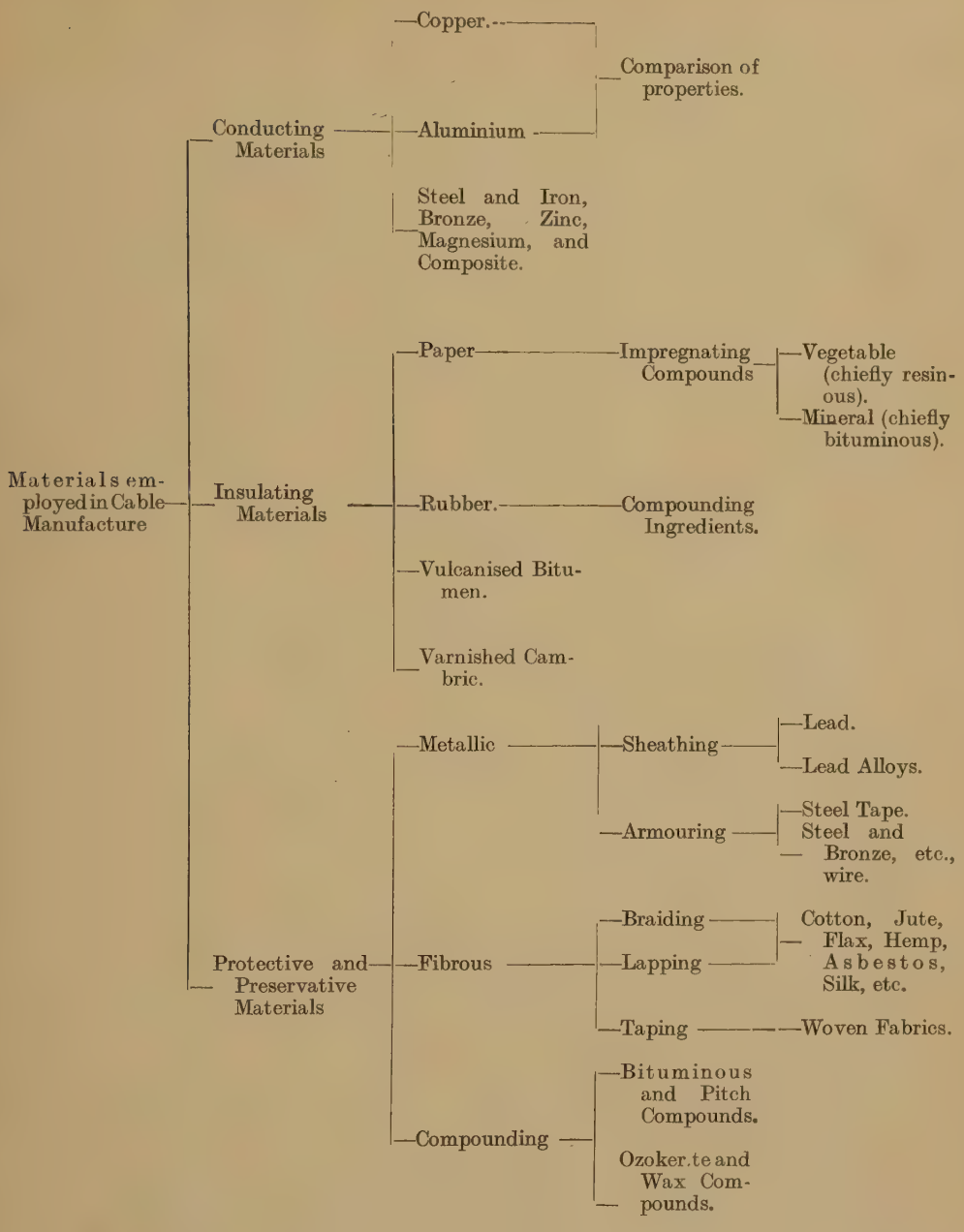
A given ingredient specified by the cable-maker might be obtainable on the market in a number of grades or qualities, and the rubber manufacturer might—in the absence of guidance and in strictly good faith, on the basis of his experience in the manufacture of other classes of goods—employ a grade which was unsuitable for electrical work. Even by the use of a constant quality—from the market classification and even from the chemical composition aspect—the variation of the source of supply of a rubber compound ingredient, entailing a slightly different process of production and possibly only a physical difference in the material, often led to trouble in the cable manufacture.

Apart, therefore, from the economics of the matter, and the natural tendency, as the cable-making industry developed and its output increased, to make the factory as self-contained as possible, the above-mentioned drawbacks constituted strong reasons for the cable-maker to extend his manufacturing resources back towards the sources of his materials so that his control over them should be at least sufficient to relieve him of such handicaps as above instanced.

At the present day the majority of the cable works include complete rubber and wire-drawing mills, while some of the larger concerns also have rolling mills for the production of the " wire rods " from which wire is drawn, and have controlling interests in rubber plantations, paper mills, lead and copper mines, and other fundamentally allied industrial tributaries which feed the cable factory, but which for various and more or less obvious reasons cannot be actually embodied therein.

In view of the foregoing, it is difficult to define at what stage the materials used by the cable-maker can be truly called raw materials, or where for the purposes of the actual construction of the cables they may be regarded as semi-manufactured.

For the purposes of this chapter the materials used in the manufacture of cables will be dealt with on the general lines of the tree index shown on the opposite page.


Materials employed in Cable Manufacture
Conducting Materials
Copper.
Aluminium
Comparison of properties.
Steel and Iron, Bronze, Zinc, Magnesium, and Composite.
Insulating Materials
Paper
Impregnating Compounds
Vegetable (chiefly resinous).
Mineral (chiefly bituminous).
Rubber.
Compounding Ingredients.
Vulcanised Bitumen.
Varnished Cambric.
Protective and Preservative Materials
Metallic
Sheathing
Lead.
Lead Alloys.
Armouring
Steel Tape.
Steel and Bronze, etc., wire.
Fibrous
Braiding
Lapping
Cotton, Jute, Flax, Hemp, Asbestos, Silk, etc.
Taping
Woven Fabrics.
Compounding
Bituminous and Pitch Compounds.
Ozokerite and Wax Compounds.

CHAPTER III

CONDUCTING MATERIALS

The early work of Matthiessen and others, directed to the establishment of standard values for the resistivity and temperature coefficient of copper, is widely known.

The "Matthiessen Standard" was, however, neither quite accurate nor universally accepted. As the result of efforts of representatives of Electrical Engineering Institutions and other bodies all over the world, an International Annealed Copper Standard was adopted by the International Electrotechnical Commission in 1913. (The actual values are quoted later in this chapter.)

In view of this culmination of the work of the early pioneers, and as their labours are referred to at length in countless works on electrical subjects, they will not be further mentioned here.

A few abstract notes on the subject of conductivity will be followed by a brief consideration of the sources, production, and properties of the various conducting materials which are at the disposal of the cable-maker.

Conductivity—conductance per unit sectional area of a conductor—is the reciprocal of resistivity or specific resistance.

The latter is the resistance between opposite faces of a cube of unit area of a material, and is usually stated in terms of ohms or microhms (millionths of an ohm) per cubic centimetre at 0° C., while the conductivity of a substance is usually expressed in percentage relation to that of copper, the most widely used conducting material.

The resistance R in ohms at 0° C. of a given conductor is proportional to its specific resistance ρ in ohms at 0° C. and to its length, L, and inversely proportional to its sectional area, S, all dimensions being, of course, in the same units; thus :—

$$R = \frac{\rho L}{S}.$$

All the ordinary pure metals have a positive temperature coefficient, *i.e.* their resistance increases with rise of temperature. In alloys, some notable exceptions occur, the well-known resistance wire manganin, for example, having a negative coefficient at temperatures above 40° C. and a positive coefficient below about 30° C., both increasing in value as the temperature variation above or below the 30°-40° C. range increases. Again, other alloys, such as "Pyro," a copper-nickel alloy used for instrument windings, has a zero coefficient.

The following table gives the volume resistivities of pure metals at 0° C., determined by Fleming and Dewar,* and their mean temperature coefficients between 0° and 100° C.:—

* *Phil. Mag.*, Sept. 1893.

TABLE I

Metal.	Volume resistivity per cubic cm. at 0° C.	Mean temperature coefficient between 0° and 100° C.
Silver (electrolytic and well annealed)	$1{\cdot}468 \times 10^{-6}$	0·004 00
Copper (electrolytic and well annealed	$1{\cdot}561 \times 10^{-6}$	0·004 28
Gold (annealed)	$2{\cdot}197 \times 10^{-6}$	0·003 77
Aluminium (annealed)	$2{\cdot}665 \times 10^{-6}$	0·004 35
Magnesium (pressed)	$4{\cdot}355 \times 10^{-6}$	0·003 81
Zinc	$5{\cdot}571 \times 10^{-6}$	0·004 06
Nickel (electrolytic)	$6{\cdot}935 \times 10^{-6}$	0·006 18
Iron (annealed)	$9{\cdot}065 \times 10^{-6}$	0·006 25
Cadmium	$1{\cdot}002\ 3 \times 10^{-5}$	0·004 19
Palladium	$1{\cdot}021\ 9 \times 10^{-5}$	0·003 54
Platinum (annealed)	$1{\cdot}091\ 7 \times 10^{-5}$	0·003 669
Tin (pressed)	$1{\cdot}304\ 8 \times 10^{-5}$	0·004 40
Thallium (pressed)	$1{\cdot}763\ 3 \times 10^{-5}$	0·003 98
Lead (pressed)	$2{\cdot}038\ 0 \times 10^{-5}$	0·004 11
Bismuth (electrolytic)	$1{\cdot}100\ 0 \times 10^{-4}$	0·004 33
Mercury (pure)	$9{\cdot}407\ 0 \times 10^{-5}$	0·000 98

As is well known, pure metals are the best conductors ; that is to say, when they contain other metals or metallic compounds, whether as impurities or deliberately alloyed with them for the purpose of obtaining other physical properties (such as tensile strength), their conductivity is lessened. Thus copper is a better conductor than the bronzes, iron than steel, and so on.

Apart from impurities or alloying components, differences arise from variations in the manufacturing treatment of a pure metal. For example, the resistivity of hard drawn copper varies with the size of the wire, *i.e.* according to the relative amounts of mechanical working and annealing it has been subjected to in the course of its production, whereas that of annealed wire does not.

Naturally, the greater the specific resistance the more the energy expended in conveying a given current.

It is therefore a commercial necessity to use, in insulated cables, conductor materials having minimum specific resistance, compatible with cost per volume. Obviously, physical and mechanical properties have to be taken into account, but from the conductivity aspect alone the electrical engineer when purchasing a cable practically buys " reciprocal ohms " (or conductance), and the cable-maker virtually selects for him a conductor material which combines to the greatest extent commercial economy and electrical efficiency.

From this point of view there are, actually, at the present time, only two metals to choose between, viz., copper and aluminium, and as they differ appreciably in specific resistance the actual choice depends on other properties, which will be compared later in this chapter.

When other requirements, such as high tensile strength and elastic limit, enter into the case, alloys such as steel or phosphor bronze, or a composite conductor made of different metals, such as copper-coated steel or composite strand of aluminium wires stranded over a steel core, may be used to effect a compromise between such requirements and those appertaining solely to conductivity. They are not, however, commonly used as insulated conductors.

A few notes on the origin and production of copper and aluminium—the most important metals from the insulated cable standpoint—and a comparison of their properties will be of interest at this juncture.

The alloy and composite conductors above referred to will also be considered in some detail.

COPPER

Evidence exists that copper was mined, smelted, and used for domestic and warlike implements in prehistoric times. Only within the last seventy to eighty years, however, has the world's output of the metal assumed anything more than comparatively trifling dimensions, the phenomenal development of the mining and refining industries connected therewith being almost entirely due to the demands of the electrical industry.

More than half the world's supply comes from the United States, the other chief producing countries being Mexico, Japan, Spain, and Australia.

Copper-bearing minerals occur in various forms in all parts of the world, usually in veins or bedded deposits.

Methods of mining vary correspondingly according to local conditions.

Apart from the native (*i.e.* metallic) variety of ore, which is sometimes found (notably in the vicinity of Lake Superior in North America), they may be regarded as divisible into two general classes, viz., the sulphide minerals (typified by " copper pyrites ") and the oxidised minerals, which are chiefly oxides and carbonates.

In districts where copper ores abound, the latter class are generally found to predominate in the upper levels ; but below the level at which water is normally encountered they are usually of the sulphide variety. Naturally, in many cases the two species are more or less mixed together.

The chief sulphide ores are :—

Chalcopyrite (copper pyrites) . .	Cu_2S, Fe_2S_3
Chalcocite (copper glance) . .	Cu_2S
Bornite	3 Cu_2S, Fe_2S_3
Fahl ore	Cu_2S, with varying proportions of the sulphides of arsenic and antimony.

The chief oxidised varieties of copper ore are :—

Malachite (the green carbonate)	$CuCO_3$, CuH_2O_2
Azurite (the blue carbonate)	2 $CuCO_3$, CuH_2O_2
Cuprite (the red oxide)	Cu_2O
Tenorite (the black oxide)	CuO
Brochantite (the oxysulphate)	$CuSO_4$, 3 CuH_2O_2
Atacamite (the oxychloride)	$CuCl_2$, 3 CuH_2O_2
Chrysocolla (the silicate)	CuO, SiO_2, 2 H_2O

The sulphide ores form the chief source of the world's supply of copper, largely because of their amenability to smelting processes.

Considerable advances have, however, been made in recent years in the utilisation of the enormous available quantities of the brochantite and atacamite ores of Chili by the more difficult " wet " processes of extraction. Generally, the treatment of the sulphide ores may be regarded as consisting of—

(*a*) Smelting, to produce a " matte," consisting of a mixture of metallic sulphides (chiefly cuprous sulphide, with varying proportions of iron sulphide), comprising the whole of the copper contained in the ore, and freeing these sulphides from silica and other earthy matter, causing the latter to be separated in the form of slag.

(*b*) Heat treatment of the matte under oxidising conditions in order to eliminate iron and sulphur, and leave the copper in the metallic state.

(*c*) Refining, to attain the required degree of purity, and/or to recover precious metals, such as gold and silver, which may be present.

Treatment prior to smelting consists of concentrating and dressing the ore by the usual metallurgical operations of sorting, crushing, jigging, and passing over concentration tables, with further treatment of " slimes " by mechanical (vibratory) treatment in " vanners " or by the more modern " flotation " processes which depend on physical phenomena.

For details of this preliminary treatment—which is designed by the metallurgist to suit the detailed conditions obtaining in any particular case—reference should be made to standard works on the metallurgy of copper.

With regard to (*a*) there is in most sulphide ores an excess of sulphur over and above the proportion required to produce a rich quality of matte, and a preliminary " roasting " or " calcining " is therefore usually employed in order to remove the excess by oxidation. In modern roasting furnaces for this operation the charge is usually raked or " rabbled " by mechanically driven arms or " rabbles," in order to expose fresh surfaces to the air in the furnace.

The smelting proper is usually carried out in blast furnaces, which is very suitable for coarse ore material, but the reverberatory type of furnace is more suitable for material in finely divided form (which has to be briquetted or " sintered " into lumps by fusion for blast furnace treatment), and as the more modern methods of concentration above referred to tend to produce a larger proportion of prepared ore

in this form, the latter type of furnace seems likely to come more into favour. (It will be noted in addition that the finely divided concentrates are more amenable to oxidation by the roasting operation.)

The prepared ore is fed into the smelting furnace with a suitable admixture of coke and fluxing material such as limestone or silicious matter, the mixture being designed with the twofold object of producing a rich matte and a readily fusible slag as free from copper as possible.

(*b*) The heat treatment of the matte for the production of crude copper is comprised of two stages which may be carried out in separate furnaces or more usually, according to modern practice, as a continuous process in a Bessemer converter having a silicious lining. The molten matte is poured into the converter and air blown through the charge. This heating under oxidising conditions causes the iron sulphide to be converted into iron oxide, which is rapidly formed into silicate by combining with the silica of the converter lining. At this stage the charge consists of cuprous sulphide and slag containing the iron, which is, in sulphide ores, the chief impurity.

In the second stage, after removal of the slag, some of the cuprous sulphide becomes converted into oxides of copper (cupric and cuprous, but chiefly the latter) and to some extent into sulphate. Oxidised forms of copper ore are often added at this stage, instead of carrying the oxidation of the cuprous sulphide to a stage where sufficient oxide and sulphate is produced from the sulphide to furnish the proportions of each necessary to react with the unaltered cuprous sulphide to produce crude metallic copper.

The chief reaction, *i.e.* affecting the major portion of the material, is represented by the following equation :—

$$Cu_2S + 2\ Cu_2O = 6\ Cu + SO_2.$$

The subsidiary reactions affecting the cupric oxide and the sulphate are represented by the following equations :—

$$Cu_2S + 2\ CuO = 4\ Cu + SO_2,$$
$$Cu_2S + CuSO_4 = 3\ Cu + 2\ SO_2.$$

When these reactions are complete the heat is raised and the copper is tapped off.

(*c*) Refining of the crude copper may be accomplished by furnace treatment or by the electrolytic process. The former consists in further heating under highly oxidising conditions in a reverberatory furnace. It is chiefly used when the crude copper contains neither deleterious substances nor compounds of precious metals such as gold or silver.

During the oxidation of the impurities in this process a certain amount of copper is converted into cuprous oxide, but this is dissolved in the copper, while the oxidised impurities are either volatilised or pass into the copper silicate slag. The cuprous oxide is subsequently reduced to metallic copper by the reducing action of gases produced by immersion of green wood poles in the molten metal or stirring therewith, the operation being known as " poling." When the oxide is reduced to a minimum, the copper attains the physical state known as " tough pitch " and is then cast into moulds.

Electrolytic refining—the separation of copper from its accompanying impurities by selective electro-chemical action—appears to be essential, however, for the attainment of the degree of purity necessary for high conductivity requirements ; and as, in addition to the elimination of deleterious elements, the process also affords facilities for the recovery of gold and silver, it has become very widely used. Electrolytic refining on an industrial scale was first carried out successfully by Elkington, who put down a plant at Pembrey, in Wales, in 1869.

The general lines of Elkington's process were followed up by others in Germany and the U.S.A.

According to modern practice an acid solution of copper sulphate, equivalent to about 3 to 4 per cent. of copper and about 12 per cent. of free H_2SO_4, is used as the electrolyte in a series of vats in which are mounted cast copper anode plates (usually about 3 ft. $\times$ 2 ft. to 3 ft. $\times$ 3 ft. and $1\frac{1}{4}$ in. to $1\frac{1}{2}$ in. in thickness, and weighing 350 to 500 lbs. according to the practice of different refineries) alternating with thin copper cathode plates of similar area. These plates are connected up to the source of current on either the " Multiple " system or the " Series " system, these terms being self-explanatory.

The former is by far the more widely employed, and is the method originally patented by Elkington in 1865. The chief general disadvantage of the latter is the higher terminal voltage required, which is a matter of some moment in a process entailing the use of conducting liquids.

The voltage in the case of the multiple system is only 0·3 volt. In this system twenty to thirty of these plates are mounted on positive and negative bus bars respectively. The anodes and cathodes are placed about two inches apart and the electrolyte is circulated through the series of vats and through subsidiary electrolytic vats in which insoluble anodes are employed for the purpose of adjusting at will the acidity of the electrolyte before returning it to the main depositing vats.

The current density employed varies in different works from 12 to 20 amperes per sq. ft. of cathode surface or even higher in some cases. At the higher values it is necessary to work at high temperatures and to circulate the electrolyte rapidly. In different works the temperature varies from about 100° F. to 140° F., and the rate of circulation from 3 to 6 gallons per minute.

Within proper limits of strength and acidity of the solution, temperature, voltage, and current density, which are the chief factors determining the selective action above mentioned, the deposit produced on the cathode plates consists solely of copper, other metals remaining as insoluble slime, collecting on the bottoms of the vats, or passing into solution in the electrolyte without being deposited. For instance, gold, silver, and lead pass into the slime, iron and nickel into the electrolyte, while other impurities are found partly in the slime and partly in solution. An appreciable amount of copper generally figures in slime analysis, but a large proportion of this is in the form in which it exists in the electrolyte, viz., sulphate, and is probably largely due to entanglement, while a further proportion is due to anode particles.

The theoretical electrical energy required per lb. of copper deposited is 0·115 kilowatt hours, and the efficiency of the process is remarkably good.

When the deposit on the cathode plates is sufficiently heavy (usually in the course of a week or ten days) they are removed from the vats and stripped of the deposit, which is next remelted in a refining furnace and treated therein on similar lines to the furnace refining above referred to, in order to bring it to the required " pitch " or physical condition. For conductor purposes it is cast into " wire bars " of trapezoidal section, usually weighing from $1\frac{1}{4}$ to 2 cwts., although for special requirements they can be made much larger. Such requirements, however, relate chiefly to conductors of large section in long jointless lengths, *e.g.*, trolley wires and overhead power lines. Insulated cables do not entail such requirements.

When the anodes are reduced to about a third of their original thickness—after about three to four weeks—they are taken out and sent for resmelting. The mud is removed from the tank bottoms and treated by various metallurgical processes for the recovery of silver and gold, and when necessary on account of becoming fouled by impurities in solution, the electrolyte is regenerated by evaporation and crystallisation of the copper sulphate.

Generally this regeneration is carried on continuously on a proportion of the main electrolyte, a certain proportion of new solution being thus continually furnished to the system.

The major portion of the world's supply of copper is now electrolytically refined, and standard market quotations for refined copper are based on the price of " electrolytic wire bars."

With regard to the purity of commercial electrolytically refined copper, slight variations naturally occur between wire bars emanating from different sources. Average values of copper content between 99·93 per cent. and 99·96 per cent. can, however, be generally relied upon in well-known brands.

The chief impurity is oxygen, which exists as Cu_2O, the only oxide of copper which can exist at the melting-point of copper (1981° F.). Traces of a number of metals occur, of which the chief are lead and iron, but such traces are usually too small to be reliably estimated. The oxygen is generally estimated by difference, and does not often exceed 0·07 per cent., and may be as low as 0·03 per cent.

With regard to the conductivity of copper when drawn into wire the following Standards of Resistance for Annealed Copper have been fixed by the International Electrotechnical Commission, and taken as the basis of normal values by the B.E.S.A. :—

I. At a temperature of 20° C. the resistance of a wire of Standard Annealed Copper one metre in length and of a uniform section of one square millimetre is $\frac{1}{58}$ ohm (0·017241 ohm).

II. At a temperature of 20° C. the density of Standard Annealed Copper is 8·89 grammes per cubic centimetre.

III. At a temperature of 20° C. the " constant-mass " temperature coefficient of resistance of Standard Annealed Copper, measured between two potential points rigidly fixed to the wire, is 0·00393 = 1/254·45 per degree Centigrade.

IV. As a consequence, it follows from I and II that at a temperature of 20° C. the resistance of a wire of Standard Annealed Copper of uniform section one metre in length, and weighing one gramme is $(1/58) \times 8{\cdot}89 = 0{\cdot}15328$ ohm.

It is apparently considered that the physical properties of annealed copper are sufficiently secured or entailed by the foregoing, as no reference is made to them in the B.E.S.A. Specification No. 7.

In Government Specification No. 1, Clause 2, however, after the customary stipulation as to compliance in all respects with B.E.S.A. No. 7, the following note is made regarding physical properties :—

" The term ' annealed ' shall denote that the wire is capable of elongating at least 15 per cent. without fracture—the test-piece being not less than 6 nor more than 12 inches long."

Again, in America, the A.S.T.M. Specification for Soft Copper Wire contains the following :—

" Physical Tests. Wire shall be so drawn and annealed that its tensile strength shall *not be greater* than the value stated in the following table, and its elongation not less than the value stated in the table," etc.

The table referred to is as follows :

Diameter, in.	Tensile strength, lb. per sq. in.	Elongation in 10 in., per cent.
0·460 to 0·290	36,000	35
0·289 to 0·103	37,000	30
0·102 to 0·021	38,500	25
0·020 to 0·003	40,000	20

With regard to Hard Drawn Copper, B.E.S.A. Specification No. 125 (1924) states :—

1. *Resistance at* 60° F.—The resistance of hard drawn copper is a function of the hardness,* and the tensile strength is an approximate indication of the degree of hardness. Within a range of from 20 to 30 tons per square inch tensile strength, the following formula has been found to express sufficiently closely the results obtained in practice, and has been adopted in calculating the resistances given in this Specification :—

$$P = \frac{T}{10},$$

where P = percentage increase in resistance of the hard drawn wire over the resistance of the wire when annealed, and

T = tensile strength of the hard drawn wire in tons per square inch.

The resistance of hard drawn copper at 60° F. (15·6° C.) has therefore been based

* For further information on this point, reference should be made to an interesting paper, entitled " Relation between the Tensile Strength and the Electrical Resistivity of commercially Pure Copper," presented by W. E. Alkins, M.Sc., at the Annual General Meeting of the Institute of Metals, March 1924.—*Jour. Inst. Met.*, vol. xxxi., No. 1, 1924, p. 157.

on the resistance of Standard Annealed Copper at 60° F., the above correction having been applied.

2. *Density at* 60° F.—At a temperature of 60° F. (15·6° C.) the density of hard drawn copper has been taken as 8·890 grammes per cubic centimetre, and the weight of one cubic foot of hard drawn copper as 554·98232 lb.

3. " *Contsant Mass* " *Temperature Coefficient at* 60° *F.*—At a temperature of 60° F. (15·6° C.) the " constant-mass " temperature coefficient of resistance of hard drawn copper, measured between two potential points rigidly fixed to the wire, has been taken as 0·0022221 =1/450·025 . . . per degree F. (0·0039991 =1/250·0055 per degree C.).

4. *Coefficient of Linear Expansion.*—The coefficient of linear expansion of hard drawn copper between 32° F. (0° C.) and 86° F. (30° C.) shall be taken at $9{\cdot}222 \times 10^{-6}$ per degree F. ($16{\cdot}6 \times 10^{-6}$ per degree C.).

Reference to mechanical tests on hard-drawn copper is made in Vol. II (" Standards ").

The rolling of bars into rods, and the drawing of rods into wire will be dealt with under " Manufacture."

ALUMINIUM

In combination with oxygen and silicon (and of course with their exception) aluminium is the most widely distributed element in nature. Unlike copper, it does not occur in the metallic state.

Its commonest form is as silicate in various clays. As oxide it occurs in the form of corundum, and as a hydrated oxide with ferric oxide, silica, etc. (in widely varying proportions), in bauxite, the chief source of alumina for the manufacture of the metal.

Cryolite, the double fluoride of aluminium and sodium, is another important form from this point of view.

Apart from the minerals which are useful in connection with the production of the metal, enormous quantities of aluminium in the form of silicates are represented in the felspars, and in the form of hydrated sulphate (alunogen and websterite), the double sulphate of aluminium and potassium (alumstone or alum rock), china clay, etc.

Rarer forms occur as the oxide in combination with other metallic oxides, such as those of zinc, magnesia, and beryllium (aluminates) ; or merely coloured by other metallic oxides, *e.g.*, ruby, sapphire, and emery, and also associated with silica and aluminium fluoride, (topaz).

It is rather more than a century ago since aluminium was first isolated in metallic form.

Oersted in 1824 produced it by heating aluminium chloride with potassium amalgam. After oxidation of the amalgam and volatilisation of the potassium, the metal was left.

Wohler in 1827 obtained it by somewhat similar means (using the anhydrous chloride, and decomposing with potassium) as a grey powder.

In 1854 Bunsen and Deville, working independently, produced the metal by electrolysing the fused chloride.

This electrolytic method, however, was not a commercially feasible one, and Deville appears to have subsequently followed the lines of other workers in purely chemical reduction processes.

The fundamental difficulty was the great stability of the aluminium compounds, by reason of which the ordinary reducing agents—carbon, hydrogen, and their compounds—failed to bring about the required reaction, and necessitated the use of metallic sodium.

Most of the processes tried on a manufacturing scale between 1855 and 1885 were therefore based on the decomposition of the chloride or fluoride of aluminium by the action of sodium. About the latter end of this period the well-known Castner-Kellner process proved effective in considerably reducing the cost of production of sodium with corresponding effect on the price of aluminium.

On account of the impurity of the metal produced from the fluoride (cryolite), Deville used the double chloride of aluminium and sodium, employing cryolite merely as a flux. At best, however, the purity attained by Deville's process was only of the order of 94 to 95 per cent., and the difficulty and cost was such that even in 1885 the world's production was less than three tons, and the price about a sovereign per lb.

From the above remarks on the stability of the aluminium compounds it will be apparent that one of the drawbacks to commercial working was the difficulty of obtaining a sufficiently high temperature, but this was considerably reduced by the introduction, in 1885-1886, by the brothers Cowles, of the electric furnace on the lines described by C. W. Siemens in 1881.

By this means the use of metallic sodium was avoided, but pure aluminium could not be produced satisfactorily by reason of the fact that, owing to the high resistance of the alumina, copper or other metals had to be mixed with the charge in order to obtain sufficient conductivity.

Considerable progress was, however, made in the production of aluminium alloys and bronzes under these conditions, and this stimulated the demand for the pure metal.

The Héroult process, patented in 1886, and first worked on a large scale at Neuhausen, introduced a principle which obviated the introduction of other metals in the charge and allowed the production of aluminium of a high degree of purity.

This principle was to dissolve alumina in cryolite in the electric furnace and to decompose it electrolytically instead of by chemical methods, thus combining electric heating with electrolytic decomposition.

In the Héroult furnace, carbon electrodes are used, the carbon lined body of the furnace forming the cathode. Consequently the aluminium settles at the bottom, from which it is tapped off at intervals of twenty-four hours or longer.

The composition and physical properties of the carbon electrodes are of great importance. The anode blocks or rods should be as free from mineral impurities as

possible, homogeneous and uniformly hard in character so as to resist superficial oxidation, and possessing high electrical and low thermal conductivity.

The electrolytic action is generally stated according to the following equation :—

$$Al_2O_3 + 3\ C = 2\ Al + 3\ CO,$$

and as a fact the oxygen of the alumina does ultimately form carbon monoxide.

It is, however, fairly certain that carbon dioxide is primarily formed, the reaction being represented by the equation :—

$$2\ Al_2O_3 + 3\ C = 4\ Al + 3\ CO_2.$$

In practice, the weight of carbon used per unit weight of aluminium produced lies between the values represented by these equations, *i.e.* between two-thirds and one-third.

The Hall process, developed contemporaneously in the United States with the Héroult process in Europe, was very similar in principle. Details of construction and arrangement of anodes differed somewhat, and the alumina was dissolved in the mixed fluorides of aluminium and calcium or aluminium and sodium instead of the double fluoride of aluminium and sodium—cryolite.

These electrical processes, which can, and invariably do, utilise cheap water-power for driving the electric power generators, and, moreover, as noted above, are capable of producing the metal in a state of great purity,* have led to a rapid expansion of the industry, and during the past thirty years the production has increased from about 1240 tons to 162,000 tons per annum (of which about 15 per cent. is estimated to be used for electrical purposes), and the price reduced from about £224 to £120 per ton.

Processes for the manufacture of electrodes and the preparation of alumina from bauxite, and improvements in construction and operation of the reduction furnaces, have each played a prominent part in this commercial development.

The properties † of aluminium are sufficiently set out in the following comparison with copper.

Comparison of Properties of Copper and Aluminium

The following Table, reproduced by kind permission of the British Aluminium Co., Ltd., affords a direct comparison of the physical, mechanical, and electrical properties of copper and aluminium :—

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* Results of analyses published by the Aluminium Co. of America show an average purity of 99·57 per cent., the impurities being given as silicon, 0·29 per cent., and iron, 0·14 per cent.

† For data regarding hard drawn aluminium wire, see B.E.A.I.R.A. Technical Report, Ref. F/T6, entitled, "Report upon Tests on Hard Drawn Aluminium Wires and Cables for Overhead Transmission Lines," 1923.

TABLE II

Property.		Aluminium.	Copper.
Chemical symbol		Al	Cu
Atomic weight (oxygen=16)		27·1	63·57
Position in electro-chemical series		14	33
Melting-point, ° Cent.		658	1·083
Melting-point, ° Fahr.		1216	1·981
Specific heat (water=1) at 20° C., cals.		0·214	0·095
Specific thermal conductivity, cals. per ° C., per sq. cm., per cm., per sec.		0·504	0·895
Approximate relative heat conductivity (silver =100 per cent.)		50	90
Coefficient of linear expansion, per ° C.		0·000024	0·000017
Coefficient of linear expansion, per ° F.		0·0000133	0·00000945
Specific gravity, rolled or drawn		2·71	8·89
Tensile strength, hard drawn wire (No. 10 S.W.G.), lb./sq. in.		26,000	50,000
Tensile strength, annealed wire (No. 10 S.W.G.), lb./sq. in.		14,000	29,000
Modulus of elasticity, lb. per sq. in.		10×10^6	$17{\cdot}5\times10^6$
Elastic limit as percentage of tensile strength		70 per cent.	75 per cent.
Specific resistance in microhms per cm. cube at 20° C. (68° F.)	Annealed	2·8159	1·7241
	Hard drawn	2·8735	1·7585
Specific resistance in microhms per in. cube at 20° C. (68° F.)	Annealed	1·1086	0·6788
	Hard drawn	1·1313	0·6924
Ohms per metre-gr. at 20° C. (68° F.)	Annealed	0·0762	0·1533
	Hard drawn	0·0777	0·1564
Resistance of solid conductor, 1000 yds. long by 1 sq. in. cross sec., ohms.	Annealed	0·0399	0·0244
	Hard drawn	0·0407	0·0249
Coefficient of increase of resistance with temperature	Per ° C.	0·00390	0·00393
	Per ° F.	0·00216	0·00218
Weight per 1000 yds. by 1 sq. in. cross section, lbs.		3,510	11,520
For H.D. conductors of equal resistance—			
Ratio of diameters		1·28	1·0
Ratio of sectional areas		1·64	1·0
Ratio of weight		0·50	1·0
For H.D. conductors of equal temperature rise—			
Ratio of diameters		1·18	1·0
Ratio of sectional areas		1·39	1·0
Ratio of weight		0·424	1·0

NOTE.—In the absence of internationally accepted standards for values of specific gravity, resistivity, and temperature coefficient, the foregoing figures may differ slightly from those given by other authorities.

Their accuracy, however, is sufficiently close for the purpose for which they are here quoted.

While, in the case of uninsulated conductors such as are used in overhead transmission lines, the comparative data furnished by the foregoing table is capable of fairly direct application, the case of insulated cables is less simple.

For example, with regard to the fundamental matter of cost, the various types of insulation—paper, rubber, and vulcanised bitumen—differ considerably in price per unit volume, in addition to which the dielectric and protective covering components vary with the fluctuation of a wide range of markets.

The bare fact that for equal resistance the weight of an aluminium conductor is half that of a copper conductor (which would give the former the advantage as regards conductivity at any price per ton less than double that of the latter) may have its apparent importance considerably modified when the ultimate comparison is between these conductors in their completely insulated and mechanically protected form; and obviously much, with regard to the comparison of cost, will depend on the size of cable and the kind of insulating material and protective coverings required in a given case, *i.e.* the relation between the cost of the conductor itself and that of the whole cable.

For example, the market prices of copper, aluminium, and rubber about the early years of the present century were such that it was possible to produce a rubber insulated cable, having a composite conductor of copper and aluminium (the latter being stranded over a copper centre), on terms of equality with a copper cable as regards conductance and cost for a given grade of insulation.

The diameter of finished cable for a given conductance was, of course, increased to some extent by this construction, but in cases where this entailed no very appreciable disadvantage, the proportions of the two metals for a given conductance value could be so designed and adjusted that the cost of the extra volume of rubber dielectric and outer coverings was compensated for by the saving effected by substituting aluminium for a part of the copper.

A technical advantage (referred to later) accrued from having aluminium in contact with the rubber instead of copper.

This construction was the subject of a Patent (Beaver and Claremont, Pat. No. 20,447/1908). Owing to altered conditions of market values the matter is now of no interest, except as an example of combined economy and efficiency in connection with the use of aluminium.

It is clear that even from the point of view of conductivity alone in the case of insulated cables it is essential that each particular case should be investigated on its merits so far as comparisons of cost are concerned.

It is, of course, conceivable that the powerful interests which are concerned with the production of each of the metals could exercise a considerable influence on such commercial comparisons.

Such considerations, however, are outside the present purview, which solely concerns the cable manufacturer and the user of his products.

With regard to the manufacturer, the case is perfectly simple, because his manufacturing operations and processes are, broadly speaking, equally applicable to cables having conductors of either metal. In fact in at least one direction, viz., in making aluminium conductors for vulcanised rubber and vulcanised bitumen cables, he is relieved of the tinning process, which is of vital importance in the case of copper conductors for similar purposes. He has, of course, to do more work in constructing an aluminium cable for a given duty ; for example, he has to draw more wire to make the stranded conductor, because of its larger diameter, and the increased volume of the dielectric necessitates the handling of more material, which in some operations, such as lead sheathing, entails a greater number of " charges " in the lead press for a given length of cable.

It will be appreciated that the extra cost of such work and the establishment charges entailed tend to mar a direct comparison on the basis of volumes and weights of materials.

With regard to the cable user, there are a number of points which he has to take into consideration in deciding which metal he will adopt, and some of these have little relation to the original cost of the cable.

For instance, in many large networks it has in course of time become imperative that every ductway in a given cable route shall be " loaded " to its maximum capacity. In fact, the situation has in some cases been such that duct-space has been the basis of design of the cable, and the margin between the diameters of cable and duct has been reduced to such an extent as to require the use of traction engines to draw the cables in. While such extreme cases are not common, and while the economy of transmission is subordinated in such circumstances to *overall* economy, the tendency of " conductance per area of ductway " to become of paramount importance in the future is not in favour of aluminium.

It is of interest to note here a point in connection with the " rating " of insulated aluminium cables as regards current carrying capacities, viz., that in consequence of the greater surface area of the cable due to the diameter of the aluminium conductor being 28 per cent. greater than the equivalent copper conductor, the dissipation of heat is better ; and therefore when temperature rise is the governing factor instead of voltage drop, the current may be increased by an appreciable percentage over that carried by a copper cable of equal conductance.

The British Aluminium Co. suggest that in consequence of this the sectional area need only be increased by 36 per cent. instead of 64 per cent., as would be necessary for equal resistance (or equal voltage drop) to that of a copper cable.

The grounds for this particular suggested figure do not, however, appear to have been accurately determined, although clearly some such compromise would in many cases be permissible.

Another view of the " conductance per area of ductway " more favourable to aluminium appears when very high pressures and comparatively small amounts of power per cable are considered.

In such cases the radius of the conductor affects, more or less sharply, the value of the maximum stress in the dielectric, and consequently the radial thickness of insulation and in turn the diameter of the complete cable.

It will be shown elsewhere in this work that the most economical design is attained in such cases when $r = \frac{E}{S}$, where r is the radius of the conductor in centimetres, E is the working voltage, and S the maximum stress in volts per centimetre in the dielectric.

When the values of E and S are such that the value of r corresponds to a sufficient area of conductor to carry the required current, there can be no objection to the use of an aluminium instead of a copper stranded conductor, from the " conductance per area of ductway " standpoint. The conditions postulated do not, however, often occur in practice.

The fact that joints in stranded aluminium conductors cannot be soldered or sweated, puts it at some disadvantage as compared with copper. Although single wires of aluminium may be easily butt-welded by means of a gas or blow-lamp flame, this becomes impracticable in the case of larger (stranded) conductors (*i.e.* joints between lengths of insulated cable) on account of the intense heat required and its effect on the adjacent insulation. (It may be noted that this latter consideration does not affect the cable-maker, as any jointing operations which may be necessary during manufacture are carried out on single wires.) Cast welded joints are open to the same objection, although excellent from the conductivity aspect, and therefore the solution of the difficulty is found in various types of mechanical conductor joints, detailed reference to which will be made in a later section of this work. Although such joints can be satisfactorily made they are naturally more bulky than a sweated joint on a conductor of corresponding sectional area, and moreover, generally speaking sweated joints are bound to be more satisfactory than mechanical ones.

The insulating character of the film of oxide on the surface of aluminium also tends to difficulties in making good contact at terminal ends, and in some cases engineers have found it economical in the case of cables of large sectional area taken into feeder pillars, etc., to terminate the aluminium cable outside and take copper tail-end cable to the terminals.

A physical point which is somewhat unfavourable to aluminium insulated cable as compared with a copper cable is its greater coefficient of expansion. It should, however, be appreciated that when—for a given current and equal voltage drop—the sectional area of the aluminium conductor is correspondingly increased, the total temperature rise will be less than in the equivalent copper cable, under similar conditions as regards surroundings, and this smaller rise may be set off against the higher coefficient. When, however, the ratings of aluminium cables are based on temperature rise instead of voltage drop (see preceding page), the risk of expansion trouble (which, as noted elsewhere in this work, is of an insidious character) is appreciably greater than in copper cables.

From such chemical points of view as relate to the interaction of the conductor

metal on ordinary insulating materials (notably rubber and bitumen), and, conversely, of components of those materials (chiefly sulphur) on the conductor, aluminium has a distinct advantage over copper, because on the one hand it does not cause deterioration by oxidation to materials in contact with it, as copper does, nor on the other hand is it acted upon by sulphur, etc., although, as will be explained elsewhere, the latter has not the importance usually ascribed to it.

Here we have an advantage which is shared by both manufacturer and user, the former—as already mentioned—being relieved of the necessity of tinning, and the latter of a potential factor in the deterioration of his rubber-insulated cables.

The highly electropositive character of aluminium, which leads to its rapid corrosion by electro-chemical or "galvanic" action when in contact with most of the common metals in presence of moisture, is naturally of much less moment in insulated cables than in other applications such as overhead lines, because one of the chief objects both in manufacture and installation is the exclusion of moisture.

Under some circumstances of use the low specific gravity of aluminium affords advantages, in spite of the increased weight of dielectric and protective coverings due to larger diameter. In addition to lightness *per se*, the ratio of tensile strength to specific gravity is very high, which is of some importance where the suspension of cables—as in pit-shaft work—is in question.

The matter of low "scrap values" for aluminium as compared with values for copper is one which has often been urged by engineers against the use of the former for use in insulated cables, but which is rather outside the present scope, being seldom argued on purely technical lines.

The foregoing comparisons may be summarised as indicating that while copper is not likely to be greatly displaced as the most efficient "all round" conductor material for the purposes of insulated cables, aluminium is a sufficiently serious rival to be worthy of close consideration in a large number of instances which occur in practice; and as the uses of insulated cables extend, and the cost of various components of them fluctuates, the choice between the two metals should, as has already been said, be made on the merits of individual cases.

STEEL AND IRON

In the early days of telegraph engineering, galvanised iron wire was largely used as an overhead conductor, either bare or covered with impregnated cotton braids for preservative purposes. As its primary function was as a conductor, it was invariably made from the purest ores of Scandinavia and Russia, and carefully smelted and refined by the well-known Swedish charcoal process. The resistance of pure iron is 5·95 times that of copper, and the excellence of the wire was such that in the galvanised state its conductivity was of the order of 96 to 97 per cent. of that of pure iron. Its tensile strength was 20 to 23 tons per square inch.

With the advent of phosphor and silicium bronzes and the improvements in the manufacture of hard drawn copper, the use of iron wire for overhead lines generally

diminished, while the cheapening and improvements in production of mild steel by the Bessemer and Siemens Open Hearth processes ousted it in other directions.

During the past few years, however, the shortcomings of steel, notably from the point of view of durability, have led to efforts to produce iron wire of great purity, with the result that there is now commercially available a certain grade of iron which is guaranteed 99·84 per cent. pure, and having in the form of annealed wire an ultimate tensile strength of 25 tons per square inch. This wire is known as " Armco " Quality Ingot Wire, and is rolled and drawn by the Whitecross Co.* from billets made by the Shelton Coal & Iron Co.

As regards conductivity it excels not only any other iron or steel, but is superior to the standard requirements of B.E.S.A. and Government Department Specifications.

The former calls for a resistance " constant " (weight per mile in lb. × resistance in ohms per mile at 60° F.), over a range of sizes, of 5328 ; whereas " Armco " wire is guaranteed not to exceed a constant of 4800.

Superior ductility and toughness also accrue from the remarkable purity of the iron.

Apart from the resistance to corrosion of the metal itself, the protection afforded by galvanising is much more effective than in the case of steel, because the spelter coating does not become more than superficially alloyed with the underlying metal, whereas steel rapidly fouls the galvanising bath, rendering the coating impure and susceptible to corrosion and disintegration.

For insulated cables, when the object is to reinforce the tensile strength of the high conductivity metal (copper), the purpose is best fulfilled by the use of steel, as the resistance of steel wire having twice the tensile strength of iron wire is only about 30 per cent. greater, or about 7·75 times the resistance of copper.

In 1921 some of the smaller flexible strands used in standard tough rubber-sheathed cables were modified on these lines by the C.M.A. as shown below :—

Area of conductor, sq. in.	Original strands. No. and diam. of wires.	New strands adopted by the C.M.A. No. and diam. of wires.
·0006	14/·0076 in.	5 tinned copper 2 tinned mild steel } 7/·012 in.
·0010	23/·0076 in.	9 tinned copper 2 tinned mild steel } 11/·012 in.

In some cases of insulated cable, such as rubber-insulated military field telegraph cable, the dominating requirement is mechanical strength, and therefore the conductor may be made almost entirely of high tensile steel (100 tons per sq. in.), and conductivity requirements may demand that only one wire in a seven-strand conductor need be of copper or aluminium.

Steel wire for such purposes may be galvanised or tinned, preferably the latter,

* Licensed under Patent No. 27201 of 1909.

because a smoother and more homogeneous coating is obtained which is less likely to occlude hydrogen from the preparatory cleaning (pickling, etc.) processes.

BRONZE

Bronzes for purposes of conduction were largely developed in France for overhead telegraph lines.

Pioneer workers in this field were J. O. Mouchel and Lazare Weiller of Paris and Havre. A considerable amount of work has also been done in Germany, the U.S.A., and in this country, in the direction of producing bronzes possessing high tensile strength and the maximum conductivity compatible therewith.

Mouchel experimented chiefly in alloys of copper and magnesium and obtained very good electrical and mechanical results.

Weiller's bronzes, however, obtained the greater vogue, and were standardised in A, B, and C, and French " telegraph " qualities, the latter having a tensile strength of about 49 tons per sq. in. and a conductivity of 30 per cent. of that of annealed copper.

Silicon (or " silicium ") bronze, so called on account of the use of copper silicide in its manufacture, was developed simultaneously in Europe and America. The outstanding feature in its composition is its comparatively large zinc content.

While zinc is rather more favourable to conductivity in a copper alloy than tin, it is less so from the mechanical aspect, and, although largely used for a number of years (chiefly for trolley-wire purposes), it could not seriously compete with the phosphor bronzes in the matter of conductivity for a given tensile strength, and has practically disappeared from use so far as conducting purposes are concerned.

The following diagram (Fig. 1) shows the general order of the results obtained by these pioneers in the production of bronze conductors, and incidentally illustrates the fact, already referred to, that high tensile strength can only be obtained at the expense of conductivity. (It will, of course, be appreciated that other mechanical properties than tensile strength, *e.g.*, such as those which bear on amenability to rolling and drawing, and on behaviour in use, enter into the matter.)

On the diagram are also marked, for purposes of comparison, average values obtained in present day manufacture of special grades of bronze wire to British Government Departments' specifications. (As these values vary over the range of sizes of wire, they have been corrected to the smallest size in general use, viz., ·046 in. diameter, 25·6 lb. per mile.)

The diagram also shows the relation of the bronzes to hard drawn copper, from which it will be clear that the sphere of usefulness of the former is practically limited to cases where current carrying considerations are subordinate to mechanical ones, as in long-span overhead telegraph lines.

Bronze wire has recently been standardised by the B.E.S.A. (Specn. No. 175/1923) on the lines of the Post Office specification, *i.e.* having 48·6 per cent. of the conductivity, a slightly greater temperature coefficient, equal specific gravity, and

40 per cent. to 50 per cent. (according to the size of wire) greater tensile strength than hard drawn copper.

As regards composition, this specification simply states that " the wire shall be a copper alloy having properties which will meet the specified tests."

The type of alloy indicated by the requirements is, practically, phosphor bronze, which is an alloy of copper and tin, containing a small amount of phosphorus. The alloying mixture, added in the form of phosphor tin, may contain traces of other metals such as zinc and lead. According to the author's analyses, the proportion of

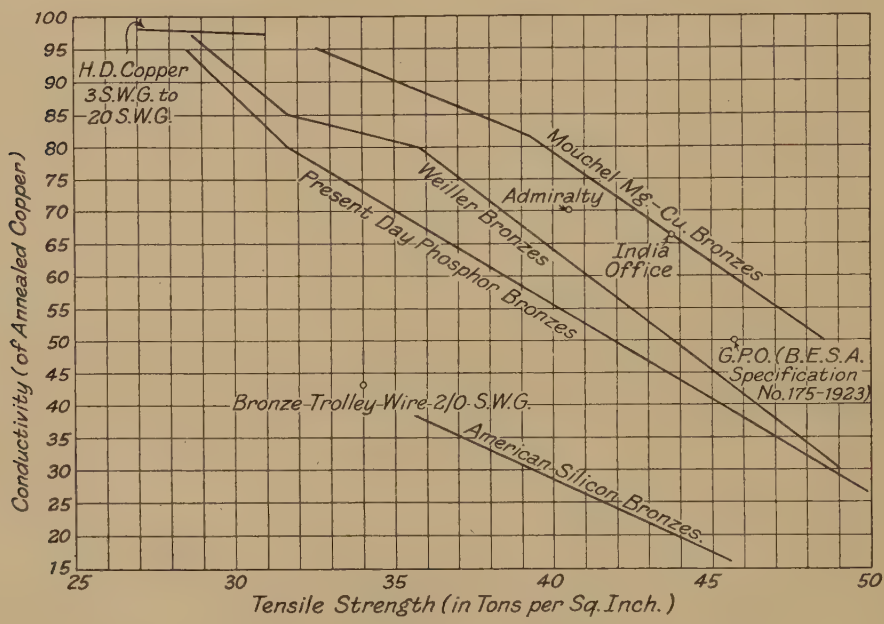

Fig. 1.—Electrical and Mechanical Properties of Bronzes.

tin does not usually exceed 5 per cent., while the phosphorus varies in different samples from 0·3 per cent. or thereabouts to a mere trace.*

As the function of the phosphorus is simply to ensure sound casting of the wire bars, its eventual disappearance by volatilisation after fulfilling this rôle is of no moment.

In this country there is some demand for a semi-insulated bronze wire for use on overhead telegraph or telephone circuits where they pass under or in juxtaposition to power lines.

The G.P.O. standardise for such purposes a bronze conductor of 55 lb. to the mile, insulated with two layers of impregnated paper, cotton lapped and braided.

The paper is specified to be treated with linseed oil, and the cotton covering

* Results of analyses on a large number of samples of phosphor bronze have been recorded by Arnold Philip, *Journ. Inst. Met.*, 1, p. 164.

and braiding to be impregnated with a mixture of red lead, linseed oil, and paraffin wax.

These coverings, of course, only constitute an emergency dielectric, temporarily preventing metallic contact in case of accident.

This type of wire is known as P.B.J., and originated in Germany.

Phosphor-bronze wires are sometimes insulated with rubber, in which case the conductor has, of course, to be tinned.

A copper-cadmium alloy having somewhat remarkable properties has recently been introduced for overhead line purposes, but has not yet come into use for insulated wires and cables.

Wire drawn from this alloy, containing only 1·1 per cent. of cadmium, is stated to have a tensile strength of 100,000 lb. per sq. in. and a conductivity of 91 per cent. ; that is to say, its tensile strength is attained with less sacrifice of conductivity than in any other copper alloy at present known.

ZINC, MAGNESIUM, ETC.

The shortage of copper and aluminium in Germany during the recent European war led to the production of zinc in the form of ductile wire, and its temporary standardisation in that country as a conductor for insulated wires and cables.

The difficulties with regard to production in wire form—which had not previously been commercially accomplished—were overcome by extrusion of the zinc in the form of wire rod, which was afterwards drawn into wire in the usual way.

Its ductility, when produced in this manner, is fairly good.

The conductivity of zinc is about 30 per cent. of that of copper, *i.e.* rather less than half that of aluminium. Its specific gravity is nearly 2·17 times that of aluminium, and only about 19 per cent. less than that of copper, so that it is by no means a commercially efficient conductor.

It is, moreover, at a further disadvantage by reason of its low melting-point (420° C.), which renders the soldering of joints in it almost impossible.

Magnesium, which was also developed as a war-time conductor material (utilising large quantities of magnesium chloride, hitherto a waste product of the potash industry), has a specific gravity of only 37 per cent. of that of aluminium and a conductivity equal to about 67 per cent. as compared to that metal. Its chief use up to the present has been for bus bars, etc., and, so far as the author is aware, it has not been used in the form of wire for insulated conductors.

An alloy consisting of 90 per cent. magnesium and 10 per cent. aluminium, called " electron," was largely used for similar purposes, and for castings used in various kinds of electrical apparatus which were required to be of non-magnetic material. Its conductivity is approximately the same as that of zinc, but its specific gravity is only about one-fourth, and its melting-point about 200° C. higher.

Other alloys such as " magnalium " (consisting of 90 per cent. aluminium and 10 per cent. magnesium) come generally into the same category as regards spheres

of usefulness, but are not likely to come into use as conductors for insulated wires or even for bare overhead lines.

A large number of alloys possessing excellent qualities in different directions are available for resistance and heating purposes. They do not, however, come within the scope of this work.

COMPOSITE

In addition to alloys, composite conductors are sometimes used, such as the well-known aluminium steel type, in which aluminium wires are stranded round a steel centre,* and the " copper-clad " type, in which a copper jacket is welded to a steel centre. The former, being stranded, cannot be made in such small sizes as the latter, which is essentially a single-wire conductor. The field of usefulness of both types is practically confined to long-span overhead transmission lines. Their employment as insulated cables is very infrequent.

The copper-clad wire is made by casting copper in annular form around a steel ingot, and by rolling and drawing processes, it may be reduced to about ·036″ diam. if necessary. Its hard wearing qualities make it specially desirable for such purposes as trolley wires, and while its stiffness is unfavourable to ordinary insulating processes, its conductivity and strength—compared to copper and phosphor bronze—will no doubt bring it into a wider field of usefulness.

It is at present made in two qualities, known as " 30 per cent." and " 40 per cent." respectively, these percentages indicating conductivity relative to copper.

Its tensile strength is about 60 per cent. greater, and its weight averages about 7 per cent. less than copper, while its elastic limit is about 125 per cent. greater.

* For details regarding mechanical properties of this type of conductor, see B.E.A.I.R.A. Technical Report, Ref. F/T13, " Report upon Tests on Steel-cored Aluminium Cables for Overhead Transmission Lines."

CHAPTER IV

INSULATING MATERIALS

PAPER

From the cable manufacturing point of view we are only concerned with the fibrous materials of the paper-maker, as insulating papers are not loaded with mineral matter, etc., nor do they require any appreciable sizing or other surfacing ingredients as do various writing, printing, or art papers.

The fibrous materials consist of various forms of cellulose, and in order, therefore, to arrive at an intelligent and impartial conception of the merits and relative suitability of the different forms for the purpose under consideration, it is desirable to briefly survey them from the chemical aspect.

Generically, cellulose may be defined as the non-nitrogenous skeleton of plant structures. The purest type, viz., cotton, is physiologically distinct in that it occurs as seed hairs (of *Gossypium*), each an ultimate fibre, all the others being constituents (in bundles or agglomerates) of stems and leaves of the various species of plant in which they occur.

A further technical distinction follows, so far as spinning the fibres is concerned (and it will be seen later that spun fibres form the paper-maker's raw fibrous material) in that the latter are actually spun in the form of bundles of ultimate fibres.

There are three modifications of cellulose generally recognised by physiologists and which are, chemically, compound celluloses, viz., the cutocelluloses, which constitute the protective tissues of plants; the pectocelluloses, of which flax is typical; and the lignocelluloses, which constitute woody tissues, and which contain a non-cellulose constituent, lignone (or lignin). The simplest type of lignocellulose is the jute fibre, which contains about 20 per cent. of lignone.

The cutocelluloses are cellular rather than fibrous and are therefore of no use for textile purposes; in fact in the production in useful form of some of the fibres (for example, flax) their isolation from the epidermal tissue occasions much difficulty. Hence the " shive " or cellular matter which is generally to be found in paper made from flax-spinner's waste.

Naturally, fibrous plant products vary more or less between the above-mentioned classes of cellulose compounds without strict lines of demarcation, and such variations depend on the part of the plant structures from which they are derived and the metabolic processes by which they are formed in each individual type, genus, and order.

The following table, based on Hugo Müller's classic analyses of raw fibres,* is intended to show how the various fibres which are available for types of paper akin to insulating paper fall under the above-mentioned physiological classification.

Relating as they do (except in the case of chemical wood) to raw fibres, the figures in the table do not actually represent the fibrous materials as they exist in

* " Pflanzenfaser," Hugo Müller, Vienna Exhibition Reports, 1873.

the final product of the paper-maker, but for the present consideration are very significant.

TABLE III

Fibre.	Cellulose.	Pectous Substances.	Non-cellulose or lignone.
	Per Cent.	Per Cent.	Per Cent.
Cotton . . .	91·35	. .	. .
Flax (Belgian) * .	70·75-81·99	9·29-2·72	. .
Hemp (Italian Sunda)	77·13-80·01	9·25-6·41	. .
Ramie . . .	62·5-75·83	12·00-6·07	. .
Manilla . . .	64·07	21·60 †	. .
Jute . . .	60·89-63·76	. .	20·98-24·32
Chem Wood ‡ (sulphite)	80-90	. .	9·87-0·73
Straw . . .	Winter Wheat . 46·6 Winter Rye . 47·69	. .	28·49-26·75
Esparto . . .	African . . 45·8 Spanish . . 48·25	. .	29·30-26·39 §
Wood ‖ . . .	Beech . . . 45·47 Poplar . . 62·77	. .	39·14-20·88 §

The preliminary mechanical and chemical processes to which the materials are subjected are aimed at the removal of the non-cellulose constituents from the various compound celluloses, and naturally the larger the proportion of these, the more drastic the treatment has to be. This entails, especially in the lignocelluloses, the risk of residual chemicals in the paper, although this risk appears to be less nowadays than formerly, presumably owing to improved methods. Apart from this, however, the resultant celluloses are not of the same constitution as chemically pure cellulose (represented by bleached cotton), those for example obtained from the lignocelluloses (jute, woods, cereal straws, esparto, etc.) being oxycelluloses, which have considerably less resistance to oxidation, hydrolysis, and other chemical reactions than those obtained from the pectocellulose group.

For example, it is well known to chemists that, in the analysis of jute, certain precautions have to be taken on account of molecular changes occurring when the fibre is dried in the water oven at 100° C.; and further, that the bleaching of jute has to be controlled with particular care in order to avoid subsequent disintegration.

* New Zealand flax—obtained from the fibro-vascular bundles of the leaves of *Phormium tenax*—is a lignocellulose containing about 83 per cent. of cellulose; whereas Belgian flax is a pectocellulose which, however, depends largely on mechanical treatment for freedom from the lignocellulose and cutocellulose substances with which it is associated in the plant stems from which it is obtained.

† Contains a proportion of ligneous substance.

‡ The figures for chemical wood are given by Griffin and Little, *Chemistry of Paper Making*, and relate to wood cellulose produced by "rapid digestion" processes.

§ Contains a proportion of pectous substance.

‖ Closely represents mechanical wood, as no chemical treatment is involved in reducing the raw wood to the pulp form in which it is used by the paper-maker.

Apart from these chemical facts, it is well known to most people that cotton and flax fabrics and papers exist which have been exposed to atmospheric oxygen for hundreds of years with little deterioration, while on the other hand the rapid auto-oxidation of paper made from or containing mechanical wood fibres has caused it to be banned for books and documents of permanent value.

From the aspect of chemical stability and resistance to oxidation and hydrolysis, the fibrous celluloses may therefore be grouped somewhat as follows :—

(1) Cotton, flax, hemp, ramie, manilla.
(2) Jute, chemical wood.
(3) Cereal straw, esparto, mechanical wood.

From this brief sketch of the chemical aspect, the desirability of restricting the composition of insulating papers to group (1) will be apparent.

Commercial exigencies, such as competition with foreign makers, have latterly forced some British cable-makers to use appreciable proportions of group (2) fibres, while Continental makers have long utilised this group only, but have latterly shown a tendency to avoid group (3), which they were apparently not averse to employing some fifteen to twenty years ago. American practice, however, appears so far to adhere closely to the use of pure manilla fibre.

Now that competition has become severe in the matter of maximum rating of cables as regards carrying capacity, and is tending to have the effect of increasing dielectric heating by causing the cutting down of dielectric thicknesses in high-pressure cables, the author is of opinion that the considerations outlined above, bearing on the durability of insulating papers, may prove to be of appreciable moment in the future.

The raw fibrous materials used in the manufacture of paper are usually roughly classified by the paper-maker according to the form in which he receives them, thus :—

(1) Rags (fibres which have been spun and woven into comparatively fine fabrics; the term, in the paper trade, refers chiefly to cotton but includes linen and ramie).
(2) Fibres (consisting of waste from spinning processes or old spun articles such as ropes, and, less frequently of course, woven material such as canvas or sailcloth; low grade grasses, straws, and other vegetable fibres also come within this category).
(3) Wood pulp.

The general requirements regarding insulating paper, such as strength, absorbency, freedom from loading or extraneous matter and impurities, limit the paper-maker to a comparatively small proportion of the fibrous material otherwise at his disposal. Although cotton is the purest commercial form of cellulose, its qualities and the comparatively fine state in which it reaches the paper-maker render it more fit and useful for fine (writing, art, tissue, etc.) papers than for the more robust pure papers demanded by the cable-maker. It would undoubtedly make the best insulating

paper as regards uniformity and freedom from imperfections, a good example of this being that sheets only 1 mil in thickness when tin coated are usable for condenser purposes. As the cost of such paper is several times that of " fibre " paper, it is out of commercial range in competition with the latter for cable-insulating purposes.

In the early days of cable manufacture, reasons of cost as well as the general requirements above mentioned led the cable-maker to the second group of raw materials referred to above, while the somewhat disastrous results which happened to wood-pulp papers in libraries and archives of different kinds, and to which a considerable amount of attention was drawn twenty to thirty years ago, tended to make him steer clear of the third group.

Undoubtedly the maxima of desirable qualities was obtainable from pure manilla fibres, but when the cable-maker called for " manilla " paper it was often loosely interpreted by the paper-maker, who had a whole range of papers classed in his trade as " manilla," the composition of which varied from pure manilla fibre only to mixtures of low-grade fibres in which manilla was hardly traceable.

As a result of stringent specifications barring the use of wood fibre or straw esparto and other fibres of the " wood " and " cereal " cellulose groups, papers which are nowadays offered as " insulating papers " seldom contain the latter. Many of them, however, contain chemical wood in admixture (up to 60 per cent. or thereabouts) with materials of the " fibre " class above mentioned.

Reference to the sources and botanical origin of various fibres, and the form in which they ultimately become available as raw material for paper manufacturing purposes, is given in the following notes.

Cotton (Genus, *Gossypium*) is obtained from the extensive plantations in America, Egypt, and India. By far the largest proportion of cotton is spun into yarn, most of which is subsequently woven into cloth.

Practically the whole of the cotton used in paper manufacture is in the form of rags, and large quantities are imported into this country, spinners' waste and fibrous refuse also contributing an appreciable proportion.

Flax (Genus, *Linum*) is obtained from a plant of the same name to be found chiefly in Russia, Italy, France, and Ireland, and is the fibrous matter of the stem.

It is used chiefly in the manufacture of linen thread, cambric, cloth, and canvas ; as in the case of cotton, the paper-makers' raw material consists chiefly of rags, spinners' waste, etc. New Zealand flax (Genus, *Phormium tenax*) is obtained from the fibro-vascular bundles of the leaves of a plant of the same botanical order (*Linaceæ*) as the foregoing.

Hemp (Genus, *Cannabis sativa*) is the fibre obtained from the stalks of the plant found growing chiefly in Russia, Italy, and Turkey. Certain varieties are cultivated in India, Africa, and other countries.

It is used largely in the manufacture of ropes, and is also woven into sailcloth and similar coarse fabrics ; old ropes, fibrous refuse, etc., form the chief source of supply for the paper-maker.

Ramie (Genus, *Bochmeria*), also known as China grass or Rhea fibre, is grown

extensively in China, Sumatra and India. It has excellent properties from the paper-making point of view, but the quantity available is comparatively small. The forms in which it reaches the paper-maker are similar to those mentioned under Flax.

Manilla (Genus, *Musa textilis*) is obtained from the leaf sheaths of a kind of palm-tree to be found chiefly in the Philippine Islands, also in India, Ceylon, and the West Indies.

It is used chiefly in the manufacture of good-quality ropes, on account of its strength, and also to a certain extent for making canvas and sailcloth fabrics.

Manilla fibre is often referred to as " Manilla hemp," but this is a misnomer, as will be observed by reference to its source of origin ; the fibre was probably associated with hemp in the early days owing to the similarity of the use of the fibres.

Old manilla ropes and fibrous refuse are the chief source of supply of the fibre for paper-making.

Jute (Genus, *Corchorus*) is obtained almost exclusively from plants growing in India ; it is chiefly used in the manufacture of coarse cloth such as sacking, and also for making ropes, although it is not suited for the latter purpose on account of its inability to withstand the action of moisture, *i.e.* liability to hydrolysis. Discarded material in the above forms and jute refuse are used in the paper mill.

Straw (Order, Gramineæ) is chiefly obtained from rye, maize, wheat, oats, and other cereals. Large quantities are imported for the purpose of paper-making ; it is seldom used, however, without admixture with other fibres.

Esparto (Genus, *Stipa tenacissimo* and *Lygeum Spartum*) is imported from Spain, Portugal, Greece, and North Africa in the form of compressed bales of grass.

Wood.—Both " mechanical " and " chemical " wood are included under this heading. The major portion of the wood pulp imported into this country is obtained from trees of the Coniferæ order, chiefly from the genera *Abies* and *Pinus*.

The manufacture of wood pulp is carried out almost exclusively in Scandinavia and North America, and as the paper-maker in this country receives both kinds in the form of bales ready for his manufacturing processes (unlike the waste materials from other industries, which require preparatory manual grading and mechanical cleaning) a few brief notes on its preparation may be desirable.

The cutting of the logs into convenient lengths (about two feet), the removal of irregular features and the stripping of the bark, is common to both mechanical and chemical wood. The latter operation is performed by " tumbling " the pieces of wood in a revolving drum fed with warm water, the bark being removed by the friction of the logs against each other.

Mechanical Wood Pulp.—The mechanical disintegration of the wood fibres is carried out by means of specially constructed grinding machinery, whereby the sides of the logs are forced by means of hydraulic pressure against a massive revolving grindstone, upon the face of which the water is allowed to flow, serving the double purpose of washing away the pulp as it is formed, and a means of controlling the temperature due to the friction.

The pulp obtained in this manner is subsequently sieved or screened in a series

of graded trays, separating the chips and coarser fibres from the finer material, the separation being assisted by a shaking motion imparted to the trays by suitable mechanism.

The next operation is the removal of part of the excessive water present in the pulp as this stage ; to attain this object the pulp is passed into a large tank in which revolves a hollow cylinder the surface of which is covered with fine wire gauze. This acts as a filtering medium through which the water passes, leaving the fibres on the surface.

The skin thus produced is then transferred to an endless length of felt, which is allowed to run in contact with the revolving cylinder ; this in turn passes through a pair of rolls which serve to expel more water, and an endless band is formed on the upper roll. This operation is allowed to continue until a layer of sufficient thickness has been produced and is then removed.

When a number of these sheets are obtained they are cut or folded into a convenient size, placed on top of each other, and subjected to hydraulic pressure, whereby the moisture content is reduced to a commercial limit. The material, which now contains approximately 50 per cent. of moisture and 50 per cent. of fibre, is sent on to the market in the form of bales.

This variety of wood pulp contains practically all the resinous, gummy, and cellular parts originally present in the tree, and the drastic mechanical treatment to which it is subjected results in considerable mutilation of the fibres.

Chemical Wood Pulp.—There are a variety of methods by which chemical wood pulp is manufactured ; the most important of these is known as the " sulphite " process, in which the general character of the operations involved is as follows :—

The log is first reduced to small chippings by means of special cutting machinery ; these chippings are then transferred to the digestors, which usually take the form of large cylindrical steel structures and are packed quite full with the wood.

A solution of bisulphite of lime is then introduced, and in what is known as the " high pressure " or " rapid digestion " process, live steam is blown through for a period of about ten hours, during which operation the wood chippings are reduced to pulp, and a considerable proportion of the ligneous matter is dissolved in the liquor. (In another process live steam is not allowed to come into direct contact with the pulp but is passed through coils, consequently the time taken to reduce the wood to pulp is considerably longer.)

The pulp is afterwards thoroughly washed and passed through a coarse sieve in order to remove any irregularities, such as knots and pieces of wood, which have not been thoroughly disintegrated. The separation is sometimes taken a step further, by passing the pulp through a series of graded screens whereby the fibres are separated into two or more classes and used according to the type of paper required. The sieves or screens are mechanically agitated in a similar manner to those used in the manufacture of mechanical wood.

The operation of separating the pulp from the water and subsequent reduction of the moisture content from about 70 per cent. to 50 per cent. by means of hydraulic pressure, follow closely on the lines already indicated in the case of

mechanical wood. Chemical wood pulp, however, is sometimes prepared in an air-dry state, and to obtain this product the pulp, after careful screening, is run into a large tank, where it is diluted with a suitable quantity of water, and subsequently submitted to a series of operations similar to those involved in the paper-making machine proper.

Physical Characteristics

With regard to physical characteristics of the various fibres, the condition in which the raw material is obtained, and consequently the treatment to which it must be subjected in the preliminary stages of manufacture, largely determine the properties of the final product. If the fibres are long, flexible, and tend to intertwine, these properties assist in attaining the desired " felting " in the formation of the " web " of paper ; on the other hand, if the fibres are short and brittle and possess no natural tendency towards " felting," the result will be a hard paper lacking flexibility and strength.

Reference is made in Vol. II to the above-mentioned physical characteristics in connection with the identification of fibres by microscopic examination. (Testing Materials.)

Paper Manufacture

The manufacturing operations of the paper-maker may be summarised for the present purpose under five general headings, viz. :—

1. Cleaning.
2. Boiling.
3. Bleaching.
4. Beating.
5. Making the paper.

1. *Cleaning.*—Materials which are of the nature of fibrous waste of various kinds usually undergo a certain amount of sorting before they reach the paper-maker's hands. In the paper mill further sorting and grading is carried out as well as the removal of obvious foreign matter. The materials are then cut up by machines, which consist in general principle of an encased revolving wheel with suitable knives attached, working against fixed blades.

Further cleaning and disintegrating processes are carried out in " willow " and " duster " machines or a machine combining the functions of both. These machines vary in construction, but in general consist of a series of revolving drums provided with projecting teeth which work against fixed teeth mounted in the frame of the machine.

The materials come from the machines in a semi-mutilated condition, free from loose dirt, and usually pass direct to the boiling kiers. In some cases, however, a preliminary washing operation intervenes.

2. *Boiling.*—The object of this process is to remove the more tenacious impurities and to soften and otherwise generally prepare the material for the subsequent operations.

The chemical reagents used are of an alkaline character, caustic soda being generally employed on account of its efficacy for the purposes in view. Milk of lime, though cheaper, is less effective, but is sometimes used when a coarse and harder product from the boiling process is permissible.

The boiling is carried out under pressure, which varies according to the strength of solution, temperature, and time of treatment. These factors vary in the practice

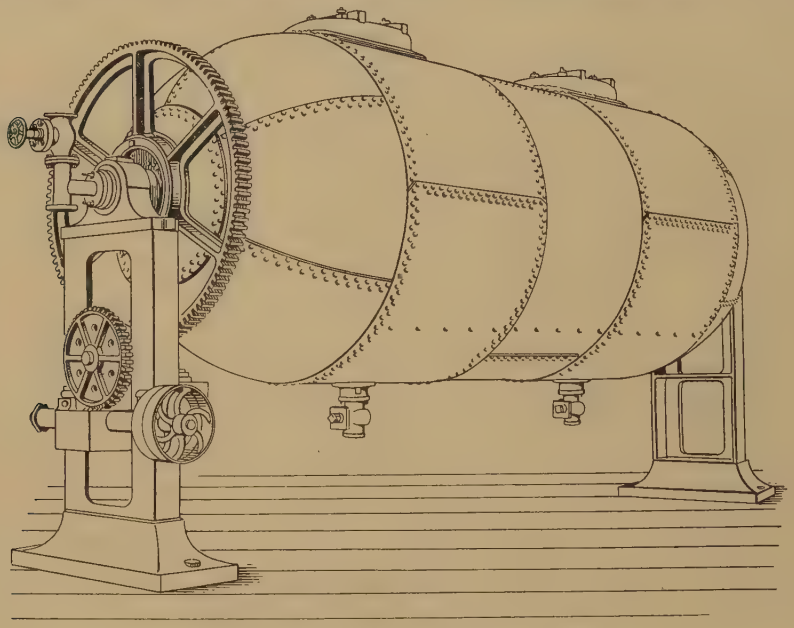

Fig. 2.—Revolving Cylindrical Boiler.

of different manufacturers, and it is further obvious that the degree of treatment required is much less in the case of materials which consist of nearly pure cellulose than in those which are highly lignified.

On completion of the boiling operation the cleaned and softened mass of fibrous material is washed with water (and incidentally cooled to facilitate handling) before removal from the boiler, and is then transferred to a " washing engine," otherwise known as a " breaker " or " hollander." This consists of an oval-shaped vessel divided into two parts by a " midfeather " or partition, which does not quite extend to the ends. On one side of this partition is a drum carrying fixed knives which almost come into contact with a similar set of knives fixed on the bed of the machine ; at this point the bed takes a gradual rise towards the knife drum, and immediately following a comparatively sharp fall to the floor level. This point is important as it is a means of controlling the circulation of the material. The drum is so arranged

that the distance between the revolving and stationary sets of knives may be varied according to the degree of maceration required.

On the other side of the " midfeather " is another drum, which is hollow and covered with a layer of fine wire gauze ; this also revolves and acts as a filter. At this stage the material is known as " half-stuff."

3. *Bleaching.*—This operation may be carried out in the washing engine, or —more efficiently and economically—in separate chambers or towers into which the pulp is pumped and circulated.

The reagent commonly used is a solution of " bleaching powder "—calcium hypochlorite ; in some cases magnesium hypochlorite, as produced in the well-known

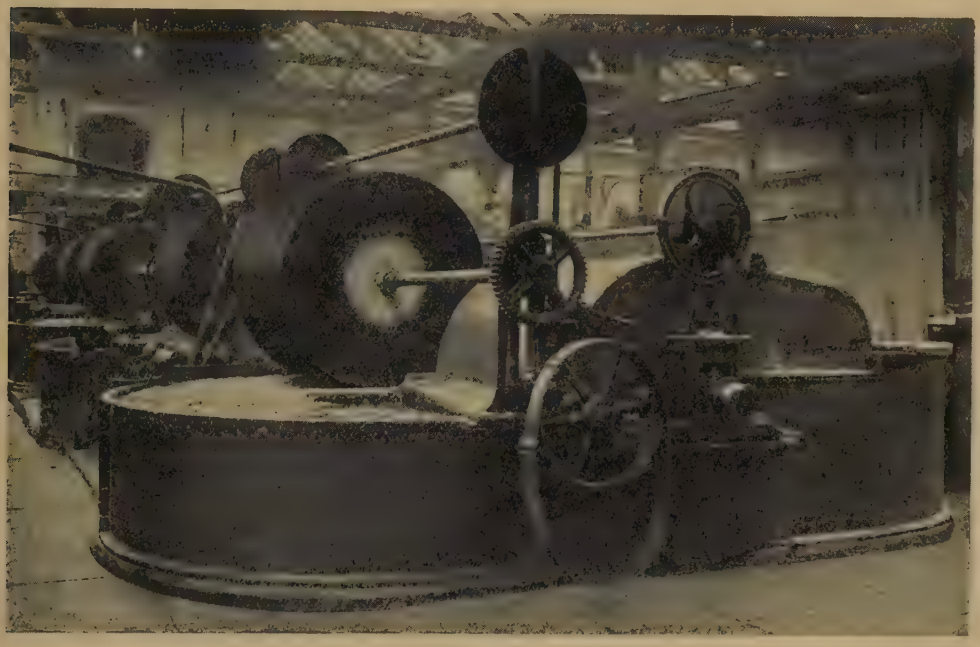

Fig. 3.—Hollander.

Hermite process by electrolysis of magnesium chloride, is employed. The action of the calcium hypochlorite is sometimes hastened by the addition of sulphuric or hydrochloric acid, causing the formation of hypochlorous acid. This has a more rapid action than the calcium hypochlorite, but is detrimental to lignocelluloses, forming chlorination products therewith.

The bleaching process effectively removes the residual organic foreign matter, but considerable care is necessary to prevent undue action which would result in weakening the fibres.

After bleaching, the fibres are thoroughly washed to remove all soluble impurities, such as calcium chloride, resulting from the action of the bleach.

It may be remarked that in insulating papers—appearance being unimportant

—little bleaching is required, and therefore the risk of residual chemicals thereform should not be appreciable.

4. *Beating.*—The next operation in the subsequent treatment of the "half-stuff" is the beating process, which is carried out in beating engines of various designs. One of the most successful beaters is based on the principle of the hollander breaker described above, with a special arrangement of the knives, and without the gauze-covered drum washer, which is of course not required.

The purpose of the beating is to ensure a more effective separation of the individual fibres, and the production of a more uniform length of fibre. This process is one of the most important in paper-making, as the properties of the final product are determined to a great extent at this stage. The character of the knives and bedplate is the dominating factor; thus if an absorbent type of paper (blotting as an extreme example) is required, a cutting action is necessary in order to reduce the fibres to short pieces, so that the capillary property is retained. On the other hand, if a hard tough paper is required, the knives would be of a blunt character, or in extreme cases stone or material of a similar nature would be substituted in order that the action would be of a rolling or milling (as distinct from cutting) nature. The varied treatment in the beater is marked by a difference of behaviour on the paper-making machine; as might be expected, the short fibres which have been allowed to retain their tubular structure part with water much more readily than the fibres which have been severely mutilated and milled.

The pulp is sometimes submitted to further treatment for the purpose of reducing the fibres to a uniform length; the machine in which this operation is carried out is known as the "refiner."

Although insulating papers are not "loaded," it may be mentioned that the addition of mineral matter for this purpose is made during the beating operation; also materials for colouring and sizing are (if necessary) added at this point. The sizing treatment—which should be reduced to a minimum in insulating papers—fulfils the purpose of binding the fibres together (and in the case of writing and printing papers, to produce an ink-resisting surface); when introduced during the beating process it is known as "engine" sizing. The materials chiefly employed are rosin and alum; the former is introduced in the form of a soap, *i.e.* sodium resinate, which is neutral; alternatively the emulsion may contain free rosin held in suspension in a fine state of division, in which case it has an acid reaction. When the resinate has been thoroughly disseminated throughout the mass, the "alum" is added; this usually takes the form of aluminium sulphate. The chemical reactions involved in this process are not fully understood, but it may be assumed that insoluble aluminium resinate is formed and that excess of aluminium sulphate results in the liberation of rosin in a finely divided state.

With regard to colouring, aniline dyes have been since their introduction largely used for this purpose; the demands of the cable-maker in this direction are, however, quite simple, as he only requires colours for distinctive purposes.

5. *Making the Paper.*—For the purpose of converting the stuff into paper the Fourdrinier machine is the premier machine in use. The first end of the Four-

drinier consists of large tanks, known as stuff chests, and into these the pulp is conducted through a large pipe from the beaters ; these tanks are fitted with a stirring arrangement by which the fibres are held in uniform suspension in the water. The necessary dilution of the pulp is carried out either in the stuff chests or may be done in a separate tank ; the proportion of fibre varies from 1 to 5 per cent. according to the class of paper. Pulp of such consistency is then passed through devices whereby foreign matter of a gritty nature is trapped, and unduly coarse fibres are retained by a number of sieves or strainers. In the manufacture of certain important varieties

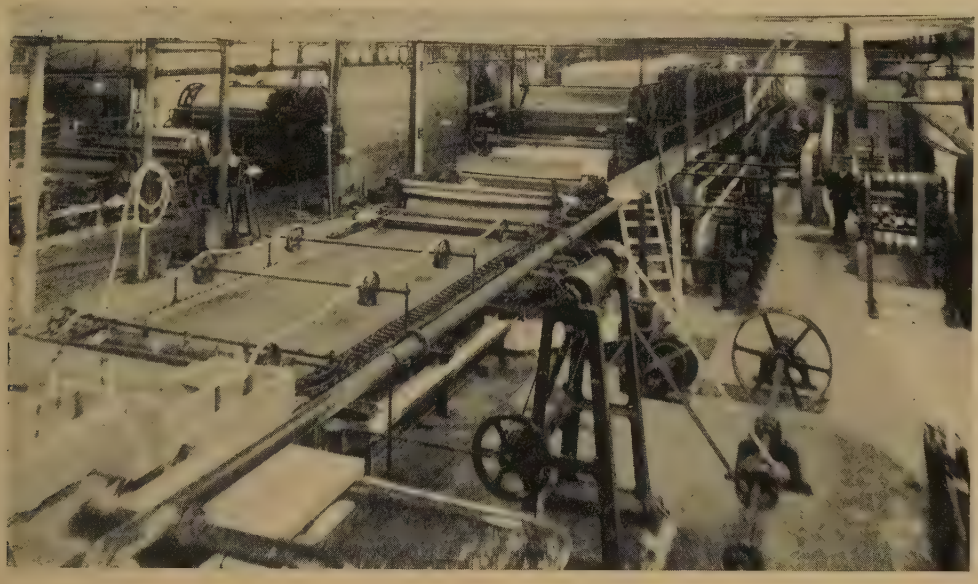

Fig. 4.—Wet End of Paper-making Machine.

of paper, such as photographic, insulating, etc., a magnetic device is sometimes introduced for the purpose of extracting iron and its magnetic oxide.

The most important feature of the paper-making machine is the moving wire table upon which the fibrous " web " of paper material is formed. It consists of an endless band of finely woven wire cloth of about 70 meshes to the inch. It varies in width, but is usually about 100 in. wide ; it is about 40 to 50 ft. in length, is supported by a large number of hollow brass rolls about 3 in. in diameter, and is held rigid by adjustable rolls underneath the machine over which it passes in the reverse direction.

The refined pulp passes from the strainers to the moving wire by means of an apron usually made of proofed cloth ; the latter extends the full width of the wire cloth and is turned up at the sides to prevent the pulp overflowing.

Adjustable brass strips run across the wire at the beginning which serve to check the flow of the fibres, and the accumulation of pulp thus formed at the back of this arrangement tends to produce more even distribution and disposition of the fibres.

" Deckle " straps, which are made of rubber of square section, run at each side and in close contact with the wire cloth ; these serve to prevent the pulp overflowing at the sides.

A graduated rocking motion is ingeniously imparted to the travelling wire, by means of suitable mechanism, for the purpose of further facilitating the intertwining of the fibres. This action is most vigorous at the beginning of the wire (or what is known as the wet end of the machine) and almost imperceptible towards the dry end. At this end the wire cloth runs in close contact with suction boxes, which are the chief means of extracting water from the web ; a small amount of fibre invariably

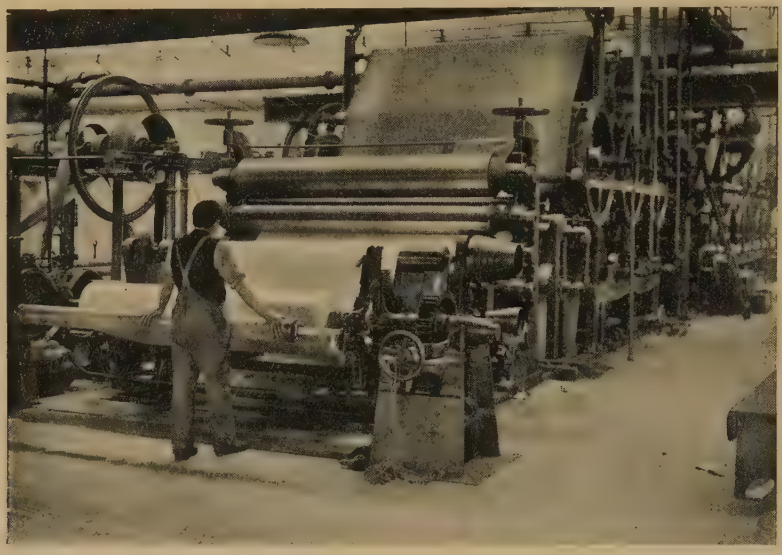

Fig. 5.—Dry End of Paper-making Machine.

passes through with the water, but this is subsequently removed and the water is then ready for further use.

Before finally leaving the wire the web comes into contact with the " dandy " roll ; this consists of a hollow cylinder, the surface of which is covered with finely woven wire cloth ; this acts on the upper surface, and has the effect of making it uniform. (Incidentally, it may be mentioned that the water-marking of writing papers, etc., is carried out on this roll.)

On leaving the wire the web passes through suction cylinders whereby the water is removed by the combined action of suction and the forcing of air through the paper.

The sheet next passes to the press rolls, of which there are usually two sets ; they consist of hollow iron drums between which the web passes, supported by an endless felt.

Subsequently the paper is run over drying cylinders, in conjunction with a dry felt ; they are made of cast iron, are of hollow construction, and usually 4 to 5 ft. in

diameter, and of which there may be as many as 35, but more usually 15 to 20. They are steam-heated, the temperature increasing gradually towards the end of the operation, and being carefully controlled throughout.

Finally, in order to produce a smooth surface, the paper passes through calender rolls, of which there may be one or more sets; they consist of a number of hollow steam-heated cylinders of large diameter, arranged vertically above one another.

From the calenders the web is generally passed through a pair of steel cylinders for the purpose of cooling, preparatory to being reeled and cut to the required width.

PAPER (AND JUTE) IMPREGNATING COMPOUNDS

Impregnating compounds, or rather their ingredients, may be regarded as being of two general classes, viz., vegetable, typified by resin, and seed and resin oils; and mineral, represented by bitumens, using the word in its broadest sense.

Of these the former is the more widely used in this country, the commonest form being a mixture of resin and resin oil, or, more correctly, a solution of resin in resin oil.

There is, however, a tendency to follow American practice in the use of mineral oil, either alone or as a substitute for resin oil in conjunction with resin, especially in the case of high-pressure cables.

In America there is a great prejudice against the use of resin, on account of its alleged undesirable effect on dielectric losses, and the general practice is to use heavy mineral oil, known as "petrolatum."

This is not a definite oil, but rather a class of oil corresponding to what is known in the oil trade as petroleum "jelly."

Continental practice tends to favour resin-mineral oil compounds. In some cases castor oil is used in place of, or as a partial substitute for mineral or resin oils. It has the advantage of securing a certain greasy consistency which is lacking in the resin-mineral oil compound, thereby ensuring that the convolutions of paper slide over one another when the cable is bent at low temperatures, and at the same time is favourable where high temperatures are encountered, because its absolute viscosity is of the same order as that of the heaviest mineral oils, and its rate of fall of viscosity with temperature rather less. Broomfield and Tawn* use it in their impregnating compound (which also contains cotton-seed pitch, gilsonite, Venice turpentine, cotton-seed oil and heavy mineral oil) designed for use in permanently hot situations on board battleships.

For ordinary conditions of use, however, most British makers employ, as stated above, a mixture of resin and resin oil, proportioned so as to suit the requirements of the impregnating process.

As mentioned elsewhere (Manufacture, Vol. II) practically all of them impregnate the paper after it is lapped on the conductor, and therefore the compound has to be thin and mobile at the temperature of impregnation. The proportions vary slightly

* Patent No. 21,334/1911.

with different makers, but 50 per cent. by weight of each ingredient fulfils this condition moderately well, and represents fairly common practice.

It will be seen by reference to Fig. 31 (Design, p. 170) that within the limits of 60 per cent./40 per cent. to 40 per cent./60 per cent. resin-resin oil, the viscosity of such solutions bears a direct relation to the resin content.

In Glover's process of impregnation, according to which the paper is treated in sheet form prior to its application to the conductor, greater viscosity is permissible than in the common method above mentioned, and a number of special oils and waxes are rendered available for use in conjunction with a resinous base. This affords scope for combining the most desirable physical properties with carefully adjusted electrical qualities, ease of penetration not being the paramount consideration in this process.

The composition, sources, and properties of a few common ingredients of impregnating compounds are dealt with in the following notes, under the broad headings above referred to, viz., Vegetable (chiefly resinous) and Mineral (bituminous).

Vegetable Ingredients

Resin.—The unqualified word " resin " is generally used to indicate " common resin." Technically it is distinguished from other resins either by the latter term or as " Colophony." In commerce colophony is invariably called (and spelt) " rosin."

It consists, chiefly, of abietic acid, together with, according to Lewkowitsch,* small quantities of abietic anhydride. Tschirch and Studer † have identified in colophony three isomerides of abietic acid, and a residue of 5 to 6 per cent. of resene after the removal of the acids. Colophony is a hard, brittle, translucent substance, breaking with a glossy, shallow, conchoidal fracture. Its specific gravity (at 60° F.) varies from 1·045 to 1·100 ; it softens at a temperature of about 175° F., and while remaining fairly viscous over a certain range of temperature, it is of a mobile consistency at about 300° F.

Its colour varies from pale amber to dark reddish brown, depending partly on its origin and partly on conditions of production ; the lighter varieties come from France, where they are chiefly obtained from *Pinus pinaster*, and the browner kinds from America, where they are obtained from the Southern long-leaf pine—*Pinus palustris*—which grows extensively in the Southern States.

The oleo-resinous juice or gum (crude turpentines) from these trees is distilled to separate the volatile portion of the oleo-resin (spirit of turpentine), and the residue is the " rosin " of commerce, the latter constituting about 85 per cent. of the original weight of the crude material.

Methods of production in America have in recent years been considerably improved and systematised. The crude method which characterised the collection of the gum in the early days was very wasteful and caused considerable damage to the

* Lewkowitsch, *Oils, Fats, and Waxes*, p. 235, Second Edition. † *Arch. Pharm.*, 241, 495.

trees ; it was known as the " box system " and consisted of cutting out a hollow cavity near the base of the tree and chipping the bark for some distance immediately above in order to accelerate the flow of gum.

This method, however, has been almost entirely superseded by the " cup system," in which vessels made of earthenware or metal are attached to the tree about three inches from the base ; V-shaped cuts are made in the bark, thus producing the flow of gum which collects in these receptacles. Under certain conditions the gum is conducted to the cup by means of a gutter or " apron," usually made of metal.

The gum as it exudes from the tree is quite clear and colourless, but on exposure to the air becomes opaque ; in order to lessen the time of exposure cups are placed at the shortest convenient distance from the incisions.

The collection of the gum extends over a period of about eight months, roughly from April to November, and the cups (which have a capacity of about one quart) are filled once in two to four weeks according to the class of tree and the weather conditions.

The cups are emptied by natives, known as " dippers," and the contents transferred to a bucket and subsequently into barrels in which it is conveyed to the still.

The still used in the production of rosin and turpentine is made of copper, and is connected through a neck with a condensing worm, which passes through a water tank, and ends above a barrel or other receptacle ; the still is heated by means of a wood fire.

A quantity of the crude gum is introduced into the still and a certain amount of water is also added to prevent charring. At a temperature of about 300° F. distillation commences, and a mixture of turpentine and water is obtained, which on standing separates into two layers ; the water of course, being the heavier, falls to the bottom.

During the distillation, foreign matter such as pieces of bark, chips, and straw, are removed by skimming.

When samples from the distillate contain only about 5 per cent. of turpentine, the operation is arrested, but allowed to proceed slowly until the last traces of turpentine are expelled from the still.

The residue, consisting of resin, is then run through a valve in the lower part of the still, but before being allowed to enter the barrels it passes through a series of graded screens which serve to remove the last traces of extraneous substances ; it is then allowed to cool, and is subsequently graded and weighed.

Resin is graded according to its colour, the paler grades of course commanding the higher prices.

They are designated by letters such as A, B, C, D, E, F, G, etc., the first three, however, are usually grouped together and sold under " B " (black), for the manufacture (by distillation) of resin spirit and resin oil.

Examples of the higher grades are " X " (extra), " WW " (water-white), and " WG " (window-glass). They are chiefly used for soap, sizing materials, etc. For

cable compound purpose there is no technical advantage in using these very pale grades, and the E, F, or G grades are usually employed.

Comparison for colour is made with a $\frac{7}{8}$ in. cube and compared against standard glass types.

In 1915 the Savannah Board of Trade issued a set of " New Rosin Standards," prepared by the Bureau of Chemistry and the Department of Agriculture of the United States of America.

The component colours for the various grades according to the Lovibond scale, used on a $\frac{7}{8}$ in. cube, are as follows :—

	Yellow.	Red.
WW	20	2·1
WG	20	2·5
N	25	3·3
M	30	4·5
K	35	5·8
I	40	7·6
H	45	9·4
G	50	15·5
F	75	34·5
E	100	52·5

The prices of resin are subject to sudden fluctuations, due to manipulative as well as natural causes ; in the markets offers are invited for particular grades, and the figure of the highest bidder is posted as the day's price.

One of the chemical properties of resin which is of considerable importance in connection with cable work concerns the facility with which it dissolves copper oxide at elevated temperatures, although without action upon it at ordinary temperatures.

This effect may be clearly seen when tarnished copper wire or strip is immersed for an hour or so in molten resin at a temperature of about 300° F., and is extraordinarily rapid at much higher temperatures.

This, together with its colloidal character (resulting in exclusion of air from any metal surface on which it may be melted) makes it an excellent flux for soldering conductor joints, etc. The fact that it has no action on copper at ordinary temperatures ensures that no after-corrosion occurs in the vicinity of the joints as happens when inorganic acid fluxes are employed. It also precludes any necessity for protecting the conductors of impregnated paper-insulated cables. The alcoholic solution of resin, however, has a distinct acid reaction in the cold, and therefore shares, for such purposes as jointing, the disadvantages of mineral fluxes.

Resin is insoluble in water, although, especially when in a fine state of division, water appears to have a hydrolytic action upon it. It is soluble in alkalis, and in organic solvents such as ether, chloroform, alcohol, benzene, amyl alcohol, acetone, coal-tar naphtha, etc. ; also in volatile oils and most of the vegetable and mineral oils.

The chief characteristic test is the acid value which is determined in the alcoholic solution by titration with alkali, using phenolphthalein as an indicator. A useful

and delicate test for the presence of resin is the Liebermann-Storch test, in which a small quantity of the substance to be tested is gently heated with acetic anhydride; after cooling, a few drops of dilute sulphuric acid (specific gravity 1·53) is slowly added, when, in presence of resin, a characteristic but fugitive violet coloration is produced. The test may conveniently be made on a drop plate, the colour being readily seen on the white porcelain background at the junction of the acids.

Resin Oil.—The lower grades of resin are redistilled in order to produce (*a*) resin spirit, and (*b*) resin oil.

The former (*a*), amounting to 3 to 5 per cent. of the original weight of the resin, distils over between 80° and 250° C. (176° and 482° F.). It is of no interest to the cable-maker, its chief use, after refining by treatment with caustic soda and redistilling, being found in varnish-making, as an adulterant of spirit of turpentine.

The latter (*b*), which distils over between 300° and 400° C. (572° and 752° F.), is, in its crude state, a dark brownish viscous oil with a marked bluish fluorescence. By taking the distillation to its farthest extent the yield of oil may amount to 85 per cent. of the original weight of the resin. As distilled, it contains a certain amount of the resin spirit—which may be expelled by heating at about 300° F.—and an appreciable proportion of the original resin, distilled over unchanged. It also contains about $2\frac{1}{2}$ per cent. of water, containing acetic acid, which, along with gases, chiefly consisting of carbon monoxide and hydrocarbons of the ethylene series, come over during the distillation.

The acetic acid is expelled by boiling with water, and the resin is removed by redistilling the oil from caustic soda solution. By careful and repeated refining on these lines it can be practically freed from resin acids.

Refined resin oil has certain uses in the textile industries, and although in itself unsuitable for lubricating purposes, is sometimes used as an adulterant in lubricating oils.

Resin grease, however, which is formed by the action of slaked lime on the semi-refined oil—depending for its formation on the presence of resin acids, *i.e.* the undecomposed resin—is a good lubricant for heavy iron bearings, such as railway waggon axles, heavy cartwheels., etc.

For the purposes of the cable-maker, three or four grades of resin oil, representing different degrees of refinement, are available. The cost of a pale, highly refined oil free from resin and traces of acetic acid is often about twice that of the common resin oil of commerce, and intermediate degrees of refinement are correspondingly valued.

The procedure of different refiners varies somewhat, so that it is possible to procure equal degrees of refinement in oils having different appearances as regards colour, and for the purposes of the cable-maker there is little point in specially decolorising resin oil. The outstanding characteristics of resin oil on which tests may be based are its specific gravity (0·96 to 0·99 approximately, at 60° F.), which is higher than that of any other oil with the exception of the "dead" tar oils, its high refractive index, which is also higher than that of any other oil, and its strong dextro-rotatory action on the plane of polarised light in the polarimeter.

Its ready solubility in various solvents such as dry acetone,* glacial acetic

* Dingler's *Polytechnic Journal*, cclviii. p. 82.

acid,* or absolute alcohol † are also distinctive. Such tests should, however, preferably be performed after saponifying and removing the resin acids, *i.e.* on the neutral unsaponifiable oil.

Vegetable Oils.—The use of these in impregnating compounds is very limited, and their function in such compounds is more in the direction of attaining some particular physical end than any electrical advantage. For example, the utilisation of castor oil for the purpose of securing a certain degree of oiliness in a resinous compound over a considerable range of temperature has already been referred to.

In the early days, the author used ben oil (expressed from the seeds of the ben-nut from *Moringa oleifera*) for a similar purpose, but although only small proportions of it are necessary this is too expensive to be commercially practicable under present day conditions.

As is well known, vegetable oils are classifiable under three headings, viz., drying, semi-drying, and non-drying. While ben oil is the best non-drying oil from the point of view of permanence, castor oil is practically the only oil in this category within commercial range; and the semi-drying oils have therefore to supply any other requirements, the drying oils, of course, being out of the question.

For the purpose in view, there is seldom much to choose between the various oils of this second group; and therefore the more plentiful kinds, such as cotton-seed or rape (colza), are usually selected.

As all the above-mentioned oils are seed oils (castor being obtained from the seeds of *Ricinus communis*, cotton-seed oil from various kinds of *Gossypium*, and rape from seeds of various species of *Cruciferæ*) their production follows the same general order of processes, viz., cleaning, hulling or decorticating, crushing, cooking, hydraulic-pressing, and the necessary chemical refinement.

Vegetable Waxes.—As in the case of vegetable oils, practically the sole reason for the use of these waxes is that they are useful for the purpose of improving the physical consistency, their merit lying in the fact that they possess high melting-points. They are, however, very expensive, and consequently difficult to obtain in a pure, unadulterated state.

At the same time, only small quantities are required to produce the maximum hardening or solidifying effect (as instanced below in the case of carnauba wax), larger proportions not producing commensurate results.

Carnauba wax is the prototype of this class of wax. It is an exudation product of the leaves of the carnauba palm (*Copernicia cerifera*), which grows in the tropical parts of South America. It is obtained by slitting the leaves and beating them, the wax becoming detached in the form of scales and powder, which is then melted and moulded into cakes.

The colour varies from greenish-brown to pale yellow, according to the degree of refinement, and is usually imported and sold in four grades, known as Waxy (or Fatty) grey, Chalky grey, and Yellows.

* Valenta, *Jour. Soc. Chemical Industry*, 1884, p. 643.
† Storch, *ibid.*, 1888, p. 136.

The following results of technical analyses of samples examined by the author illustrate the relative differences between these grades.

	Waxy Grey.	Chalky Grey.	Yellow.	Yellow.
M.P. (Cap, Tube)	181° F.	180° F.	180° F.	182° F.
Moisture . .	0·13%	3·25%	1·68%	1·21%
Ash . . .	0·49%	0·11%	Trace	Trace
Residue * . .	2·45%	1·56%	0·7%	0·6%
Colour . .	Greenish-brown	Chalky yellow	Dull yellow	Yellow

With regard to the hardening effect of the admixture of carnauba wax above referred to, a pale yellow grade will increase the melting-point of an ordinary pure paraffin wax of 130/132° F., M.P. by about 22° F. when added to the extent of 5 per cent., but the addition of three times this quantity will only raise the melting-point a further 12° F. Above 15 per cent. the effect on the melting-point is practically negligible.

Candelilla wax, also a plant excretion (from *Euphorbia cerifera* and other shrubs indigenous in Mexico and the southern parts of U.S.A.), is useful to a certain extent on the lines of carnauba wax, but its melting-point only averages about 165° F., and varies appreciably in different parcels.

Carnauba and candelilla are practically the only vegetable waxes suitable for the above-mentioned purposes which are at all freely and regularly available in Europe in the ordinary way of commerce.

Japan wax—which is chemically a vegetable fat, and not a wax—is very occasionally used by the cable-maker, but as its melting-point is only about 132° F., *i.e.* no higher than that of a good paraffin wax, and only differing from it in degree as regards crystalline structure, it has little or no advantage technically over the latter.

It is obtained from the fruity portion of certain berries lying between the skin and the kernel, and is extracted by crushing, steaming, pressing, etc.

Mineral Ingredients

Materials of bituminous origin play an important part in the manufacture of impregnating compounds. The word bituminous is here used in the strict chemical sense, as, in the author's opinion, it should be when discussing raw materials.

Bitumen is perhaps best defined as a class of minerals which occur naturally, in gaseous, liquid, and solid forms, consisting chiefly of compounds of carbon and hydrogen (but sometimes containing compounds of nitrogen, sulphur, and oxygen), which are soluble in chloroform and other organic solvents.

* Solid matter settling out on allowing the molten wax to stand for some hours; chiefly organic in character.

Taking a broad view of the various substances which should, according to the foregoing definition, be classified under the generic term bitumen, we have :—

Gaseous	(*a*)	natural gas.
Liquid	(*b*)	natural naphtha or " rock oil."
,,	(*c*)	petroleum.
Semi-solid	(*d*)	Maltha, or mineral tar, which may occur by itself or in conjunction with earthy matter, as in bitumen-impregnated rock, etc.
Solid	(*e*)	Ozokerite " earth wax " or " natural paraffin."
,,	(*f*)	Solid bitumens, varying from (1) pure hydrocarbon substances, practically free from mineral matter, such as manjak, Gilsonite, Grahamite, etc. ; through * (2) bitumens containing mineral matter more or less chemically combined, typified by Trinidad and Cuban bitumen ; to (3) bitumen-impregnated sandstone or limestone rock, represented by the well-known Seyssel, Val de Travers, Limmer, Ragusa, Oklahoma, and other deposits.

The nomenclature of bituminous substances does not, however, even in technological circles, follow the scientific definition ; for example, many writers use the word " pitch " as a synonym of bitumen when referring to substances included under (*f*) (1) above. In the author's opinion " pitch " should be taken to indicate a residue of distillation, *i.e.* an artificially produced—as distinct from a naturally occurring—substance.

In trade circles the relation between strict definition and nomenclature becomes hopelessly lost, for example, the type of solid bitumen (*f*) (1) is usually called " asphaltum " in the varnish, japan, and chemical trades ; the type referred to under (*f*) (2) is practically the only one known in the cable trade as " bitumen," and that under (*f*) (3) is commonly known as asphalt. Again, any of them may be known in commerce by their geological name or by some special name indicating their geographical origin, or simply by a trade designation.

To avoid the confusion which must arise when a generic term such as bitumen is also commonly used to denote a small section of the substances embraced by it, and even then in a manner which is not consistent, it will be advisable in the present work to follow the definition indicated above (including the suggested restriction as to the use of the word " pitch ") while keeping in view the true relations of the substances included therein.

From the point of view of impregnating compounds, the cable-maker is chiefly concerned with materials derived from (*c*), (*e*), and (*f*). Those under (*c*) include mineral oils, paraffin wax, and petroleum pitch ; under (*e*), refined ozokerite and cerasin wax.

With regard to (*f*), we may for the present purpose exclude those containing

* There are, of course, intermediate varieties, such as hatchetin or " mineral tallow," elaterite or " mineral caoutchouc," etc.

any appreciable amount of natural mineral matter after refining to a reasonable condition of freedom from extraneous substances. Other types are chiefly of interest to the cable-maker in connection with the laying and protection of cables, and they will receive further attention under those headings.

(*c*) Liquid petroleum is found in many parts of the world. The United States of America, however, supply the major portion of the world's output.

The following figures show that during the period 1913 to 1923, the world's production increased by approximately 150 per cent. They also show the effect of the Great War on European sources of supply and mark the entry of new sources (under British control), such as the Persian and Egyptian oilfields, which are now being rapidly developed. Owing to the great preponderance of American and Mexican production, however, the centre of gravity of the world's supply remains at present unaffected.

TABLE IV

WORLD'S PRODUCTION OF CRUDE PETROLEUM

(*Expressed in tons*)

Country.	1913.	1923.
United States	35,492,319	98,000,000
Mexico	3,670,899	22,309,253
Russia	8,976,336	5,228,356
Persia	243,621	3,289,474
Dutch East Indies	1,534,223	2,083,333
Roumania	1,885,225	1,466,216
India	1,107,821	1,010,000
Peru	304,752	850,000
Poland	1,113,400	684,931
Sarawak	19,953	547,465
Venezuela	..	567,164
Argentine	18,660	477,941
Trinidad	70,506	428,750
Japan and Formosa	274,844	226,000
Egypt	12,618	138,267
France	..	69,861
Colombia	..	63,582
Germany	140,000	49,859
Canada	32,583	23,333
Czechoslovakia	..	13,889
Italy	6,564	4,444
Algeria	..	1,268
England	..	133
Others	295,563	26,667
Total	55,199,887	137,560,186

The character of crude petroleum varies according to its source, being in some cases light coloured and fairly pure and therefore requiring little treatment to prepare it for use, but in others dark coloured and relatively impure.

From the point of view of chemical composition, petroleums may be divided into paraffin-base and asphaltic-base oils.

The former, of which Pennsylvania oil is typical, largely consists of open chain hydrocarbons of the saturated paraffin series, $C_nH_{2n}+_2$, while unsaturated cyclic hydrocarbons of high molecular weight are characteristic of the asphaltic-base oils of California.

It is of interest to note that crude Russian (Baku) oils differ from the above-mentioned American oils in that they consist chiefly of hydrocarbons of the C_nH_{2n} naphthene group, which constitutes a transition from the fatty hydrocarbons (paraffin series) to the aromatic hydrocarbons (benzene series).

These distinctions have a relation to the cable-maker's materials referred to above as derived under (*c*); mineral oil being obtained by distillation (as lubricating oil) from crude oil of the Pennsylvania or Russian types (the California type being chiefly used for fuel purposes), paraffin wax from the Pennsylvania type, and petroleum pitch from the asphaltic-base oils.

The distillation products of crude petroleum may be broadly classified in the following order :—

Motor spirit (gasolene)
Illuminating oils (kerosene)
Lubricating oils (light and heavy), and
Residue.

The yield of the respective fractions is determined primarily by the character and composition of the crude oil, which in turn (as just noted) depends upon its origin, and secondarily, by the method of distillation employed. Within limits the process of distillation may be varied in order to increase the yield of certain products according to the prevailing market values.

From the point of view of impregnating compounds, the cable-maker is only interested in products obtained subsequently to the distillation of the motor spirit and illuminating oil fractions, and only a brief reference to methods of removing these need be made. The processes generally used fall under two headings :—

(*a*) Intermittent, and
(*b*) Continuous systems;

which are further divisible into :—

(1) Dry distillation, and
(2) Steam distillation.

The source of heat may be oil, gas, or coal, according to the location of the plant and the relative facility with which they are obtainable.

(*a*) *Intermittent Systems.*—(1) This process is also known as the "cracking" process, and is generally used for the treatment of non-asphaltic petroleums on account

of the higher percentage of lighter products (*i.e.* low boiling-point constituents, such as motor spirit, illuminating oils, etc.) produced by the " cracking," or chemical breaking down of the higher boiling-point constituents, consequent upon prolonged heating at elevated temperatures.

(2) The introduction of dry steam during distillation (when the contents of the still are above the boiling-point of water) has the effect of aiding evaporation of the lighter constituents and diminishing dissociation of the heavier constituents. In some cases the distillation is carried out under a reduced pressure in order to further facilitate the process and to minimise molecular changes in the chemical structure.

Fractionating towers are sometimes introduced in this system, from the bottom of which the various fractions are withdrawn.

(*b*) *Continuous Systems.*—(1) The " topping " process is one of the most successful methods operated on this system.

The essential feature is the separation of the lighter fractions from the heavier oils.

This is carried out by injecting the crude oil (which has previously been heated) into the top of a vertical cylindrical chamber, down which it is conveniently directed. The inner construction of the chamber provides a large surface area, and this facilitates vaporisation of the more volatile portion, which escapes through a suitable exit at the top of the chamber, and subsequently passes through a water condenser, the heavier portion falling to the bottom, where it is withdrawn.

The consistency of the residue depends on the crude oil and on the degree to which the distillation is carried, and may be almost solid at normal temperature.

(2) In another successful process the apparatus consists of a number of cylindrical vessels fixed horizontally and connected in series.

The crude oil, after a preliminary heating in order to remove moisture and other foreign matter, flows at a constant rate into the first tank, where the degree of heating is regulated according to the fraction it is required to vaporise.

The vapours pass from the still through a worm condenser and are collected in a suitable receptable. By a convenient arrangement of connecting pipes the residual oil passes to the next still, where a greater heat is applied, and a correspondingly higher fraction is removed and collected. The process is repeated, and such factors as the number of stills in the system, temperatures, etc., determine the composition of each fraction, and also that of the residue which is drawn from the last tank.

Lubricating (*Insulating*) *Oils.*—When the more volatile portion (motor spirit) and illuminating oil has been removed, the contents of the still are known as " residuum," and in the production of lubricating oils it is at this stage transferred to a special type of vessel, known as a tar still. The charge is then subjected to distillation, and the various distillates, which increase in gravity and darken in colour as the process progresses, are collected.

The fractionated oil is now submitted to refining processes, for which purpose it is transferred to an agitator, which consists of a large iron tank, lined with sheet lead, and having a suitable arrangement for the introduction of air at the lower end, for the purpose of keeping the contents in motion.

The first treatment consists of agitating the oil with a small quantity of con-

centrated sulphuric acid; this removes tarry matter and certain other substances of a foreign nature. The combination of tarry matter with the sulphuric acid produces "acid sludge," and this is removed through stop-cocks at the lower end of the apparatus.

Subsequently water is introduced into the apparatus, the contents agitated, and the water drawn off.

The oil is next treated with caustic soda solution (approximately 1 per cent.) and the contents of the tank again agitated. After finally washing with water, the oil is transferred to settling tanks, and after allowing to stand for a certain period, a fairly clear oil is produced.

In some cases where the necessity arises for a specially pure lubricating oil, the product is filtered through animal charcoal. The filters take the form of specially constructed tanks, which are usually heated by steam or hot air (flue gases), in order that there shall be no risk of overheating and consequent discoloration of the oil.

The limpid mineral lubricating oils are usually referred to as "spindle oils," and the viscous varieties as "cylinder oils," and the medium grades as "machine oils"; these terms are quite arbitrary, and there are no generally accepted technical definitions.

The interest of the cable-maker in the foregoing processes of distillation and refinement lies in the probability that as they affect the chemical composition and physical properties of the products, so also are they likely to affect the electrical properties.

For example, it is known to oil chemists that with regard to lubricating properties refinement by filtration is preferable to acid treatment, as although the residual acidity in the latter case may be negligible (as indicated by chemical tests) there is a tendency in course of time to slight separation of colloidal substances, forming under some conditions an appreciable sludge. Similar formations are well known to electrical engineers in connection with transformer oils, and the difference between various oils in this respect is also a matter of common experience. It follows that similar considerations are more or less liable to affect the cable-maker's purposes, and although it is not feasible for him to exercise much influence on the refiner's methods, it behoves him to take great care in the selection of such standard grades and qualities on the market as will comply with his requirements.

The usual method is for the cable-maker to determine the physical and chemical properties of the oils which suit his requirements and to issue a specification based thereon.

The specified data usually relate to specific gravity, viscosity, and flash-point (in addition, of course, to chemical neutrality), and to this extent are in line with the custom of the oil trade. It is, however, incomplete for the positive identification of an oil, as several brands may be found to give practically identical figures for these properties under standard conditions of test and yet have appreciable differences under conditions of use. The missing link—as pointed out by the author many years ago *—is the superficial tension of the oil, which probably depends not only on

* *Electrical Times*, 18th November 1909, p. 507.

the molecular composition (and therefore may be characterised, as already indicated, by the source of the crude oil) but also on methods of refinement; and just as the mechanical engineer further subjects his oil to tests in special testing machines to determine its intrinsic "oiliness" (or the property referred to by Thurston as combined capillarity and viscosity) so the cable-maker should employ a surface tension test to complete his control facilities.

Paraffin Wax.—The paraffin wax of commerce is obtained during the process of refining petroleum and shale oils, the percentage yield from the latter being much greater than from the former.

It is composed of saturated hydrocarbons of the series C_nH_{2n+2}, and it is noteworthy in connection with what has already been said (p. 76) regarding the composition of mineral oils that Russian oils contain no paraffin, while American petroleum yields about 3 per cent.

There are two general classes of paraffin wax on the market, viz., "spirit" refined and "sweated" refined, these terms obviously indicating the methods of refining. Both are graded for selling purposes according to melting-point.

The author prefers to use the spirit refined type, as the sweated product is usually contaminated with sulphur, and is electrically less reliable, apart from being chemically undesirable. Spirit refining is practically confined to American practice, the Scottish shale and Galician petroleum products being almost invariably sweated refined.

In all cases it is produced by freezing out from certain fractions of oil during the refining process, the separated crude wax being collected and the oil expressed from it in filter presses, at which stage it is known as paraffin scale. There is a large market for it at this stage, but for purposes demanding a more refined product it is either—in the case of the sweated refined type—subjected to heating and further filtration, or dissolved in a solvent, such as petroleum spirit, from which it crystallises out on cooling. These processes are repeated according to the degree of purity required.

The melting-point varies according to grade from about 100° F. to 140° F., a good reliable grade of spirit-refined wax being that marketed as 130°/132° F. melting-point, or, more accurately, setting-point.

The specific gravity varies from 0·79 to ·094, according to origin and degree of refinement.

Petroleum Jelly (very commonly but erroneously termed Vaseline) is obtained by concentrating the residuum of the crude oil remaining after distillation from either paraffin base or asphaltic base crude. The latter is the more abundant and widely distributed.

The resulting product is dissolved in petroleum spirit and refined by treatment with animal charcoal (the solvent being subsequently evaporated) in the case of the paraffin base, but it is also necessary to use acid in the case of the asphaltic base crude. This, of course, is an important difference, and the use of the paraffin base product is always to be preferred, because it eliminates the possibility of the existence of residual acid.

There is also considerable variation in the consistency and general characteristics, depending on the type of crude and method of refinement; for example, these is a distinct difference in the colour of the products obtained from the two types, especially in the lower grades, and this is best exemplified by examination of the surface of a freshly melted and cooled sample. In the case of the paraffin base product the colour is distinctly greenish, whereas the asphaltic base jelly possesses a brownish colour.

The paraffin base crude is located chiefly in Pennsylvania, and products from this source are comparatively scarce, and command a premium against the products obtained from asphaltic base crude.

Petroleum jelly is usually classified under the heading of Dark Green, Red, Amber, Yellow, Cream, and White—the three latter are higher grades which are the product of repeated filtration operations, used chiefly for medicinal purposes.

Although the cable-maker usually regards viscosity as the most reliable check for ensuring uniformity of supplies of a given selected grade, the American refiners do not as a rule accept this as a basis of sale, the melting-point being the generally accepted commercial standard.

Petroleum Pitch is the residue resulting from the distillation of asphaltic petroleum.

The physical character of the residual products vary considerably, firstly on account of differences in composition of crude petroleum, secondly on the mode of distillation employed and subsequent treatment of the residue.

In the " topping process " and " steam distillation process," both of which are extensively used for the distillation of asphaltic petroleums, the operation is allowed to proceed until the residue is of the correct consistency, and under such circumstances the resulting product is known as a " straight " pitch. It is necessary to exercise great care during the process in order that the temperature shall not become excessive, otherwise " cracking " and consequent alteration in the chemical composition and physical properties are produced. Where the distillation has been carried too far, the desired consistency is often obtained by the addition of a proportion of the heavier distillate (oils). Overheating to any appreciable extent is usually accompanied by the production of carbonaceous matter (fixed carbon) in the residue, and its presence in a sample is indicative of a " softened " product.

A variety of petroleum pitch, termed " blown " pitch, is produced by the oxidation of residual oils or sludge.

The operation is usually carried out by blowing with air at a fairly high temperature, and the final product varies according to the time and temperature of such treatment.

Blown products are sold under various trade names, such as Hydrolene, Byerlite, etc.*

One of the advantages claimed for this type of petroleum pitch over the " straight " product is that it possesses a tougher consistency, and is consequently less brittle, whilst it retains a softening-point at least equal to, and in some cases

* Abraham, *Asphalts and Allied Substances*, 1918.

considerably higher than, the corresponding " straight " pitch, obtained from the same residue.

The effect of sulphur on petroleum residues at elevated temperatures is analogous to that of oxygen, inasmuch as it produces a similar condensation product.

On account of the higher cost of production of the sulphurised product, however, it may be said to have been entirely superseded by the oxidised or blown product.

The reaction with sulphur is, however, of considerable technical value in connection with the employment of petroleum pitches in rubber and vulcanised bitumen compounds.

(*e*) *Ozokerite* occurs naturally in various parts of the world, but so far as the supply to this country for cable manufacturing purposes is concerned, the chief source is Galicia.

It belongs to the olefine or C_nH_{2n} series, but also contains higher members of the C_2H_{2n+2} series, as might be expected from the fact that petroleum of the paraffin base type is almost invariably found in the strata underlying the deposits. As mined, the wax sometimes contains 10 per cent. or even more petroleum, which causes it to have a pronounced, though not unpleasant odour : the word ozokerite is, in fact, derived from two Greek words signifying " to smell " and " wax."

There is a great lack of uniformity in the material in its natural state, both as regards appearance and physical properties. In the Galician field alone, for example, six or seven well-defined varieties are found, varying from hard and yellowish to soft and black.

The grade from which the material used by the cable-maker is chiefly drawn is a moderately hard black or brownish kind, which is, in its raw state, more or less contaminated with earthy and mineral matter, and is known as " lep." This variety does not usually occur in surface veins or fissures, but has to be mined.

The mined wax is first subjected to a process of hand-picking, and subsequent treatment depends upon its degree of freedom from impurities.

The lep is placed in large wooden vats filled with water, and agitated by means of a paddle. In this operation a large proportion of the mineral matter is dissociated from the mass and either sinks to the bottom or remains in suspension.

The waxy content, on account of its lower specific gravity, floats on the surface, and is skimmed off, the operation being repeated until no more wax separates.

The crude wax obtained in this manner is then melted, when a further separation of impurities occurs.

In cases where the foregoing procedure is not successful, resort is made to the use of hot water, and the molten wax is skimmed off the surface. In the preliminary separation the contents of the pan are not stirred, in order to prevent the finely divided mineral matter rising to the surface. When the major portion of the wax has been removed, however, stirring is permissible, but the contents are allowed to settle before the remaining wax is collected.

The separated wax obtained by the above methods, along with the hand-picked wax previously referred to, is now in a condition suitable for final treatment.

This consists of heating the wax and allowing it to remain molten for a sufficient length of time for the finely divided mineral matter to subside, when the wax is run off into moulds, in a comparatively pure condition. The refined material is still brownish-black in colour, but its odour is less pronounced, and it has a characteristic plastic, waxy consistency. Its melting-point is approximately 125° F.

Cerasin.—A considerable quantity of refined ozokerite is subjected to further treatment and converted into cerasin wax.

There are two varieties, viz., yellow or ordinary, and white or bleached cerasin, the latter entailing an additional process.

In the first place the refined ozokerite is freed from moisture by maintaining it at a temperature of 250° F. for the necessary period.

The refining process consists in treating the dried wax with concentrated sulphuric acid, and it may be carried out at different temperatures, and with various proportions of acid. The action of the acid is to destroy the colouring matter, and where a temperature of 250° F. is not exceeded, a black tarry mass is formed, which sinks to the bottom of the vessel.

In a variation of the above process the mixture is subjected to a higher temperature, whereupon the tarry mass is decomposed with the evolution of sulphur gases. It is claimed that the oxidising action of the acid at the more elevated temperature is more efficacious.

The residual acid in the wax is neutralised by the addition of substances of a basic character, and after allowing the contents of the tank to stand for a certain period (usually about 24 hours), the wax is drawn off, and if desired may be treated with a suitable bleaching or decolorising agent.

The final process consists of filtering the wax, and this is most efficiently carried out by treatment in filter presses ; the product is then run into moulds, and is usually placed on the market in the form of thin cakes wrapped in paper.

The specific gravity of cerasin is approximately ·920, and the melting-point varies between 140° F. and 176° F. It has a peculiar feel when rubbed between the fingers, although the plastic consistency characteristic of ozokerite is considerably modified during its conversion into cerasin. Unlike paraffin, however, it is not crystalline in character, and this is an important difference from the cable-maker's point of view.

Unfortunately there is no difference in the chemical composition of cerasin and paraffin, consequently adulteration of the former with the latter is common. Any considerable addition of paraffin may be detected by its tendency to lower the melting-point, and in some cases the specific gravity.

Adulteration with resin is also quite common, in fact, simple mixtures of paraffin and resin are frequently offered as cerasin. The presence of resin is easily demonstrated by the Liebermann-Storch reaction, previously referred to (p. 71).

Other common adulterants are heavy mineral oils and saponifiable fats such as tallow, stearine, and the like. Sometimes proportions of expensive waxes such as carnauba are used to disguise the presence of adulterants, by hardening the product.

It is, in fact, difficult to obtain cerasin free from adulteration, the major portion

being utilised to suit particular purposes, *i.e.* as substitutes for more expensive waxes, or degraded in various ways for purposes of competition.

Montan Wax.—This does not occur naturally, but is extracted from the lignites of Saxony and Thuringia.

It is stated to consist of montanic acid and alcohol.

It may be refined to a white waxy state, rendering it available for general use in the wax and candle industry.

This refinement, however, is of no advantage to the cable-maker, as for practical purposes it amounts to little more than decolorisation by the elimination of pitchy matter.

The crude wax is comparable with ozokerite from the cable-maker's point of view, but although there is a marked resemblance as regards colour, it is physically quite dissimilar, having a much higher melting-point (about 175° to 180° F.), and being brittle rather than plastic.

It is little used in this country, and so far as its functions in impregnating compounds are concerned, it is in the same category as carnauba wax, *i.e.* they only relate to physical consistency and the enhancement of melting or softening points.

Montan pitch, one of the by-products of the refining process above referred to, is sometimes used in cable waxes for the external preservation of cables.

(*f*) *Asphaltum.*—The grades of solid bitumen practically free from natural mineral matter, and characterised by high melting- (or softening-) points, bright conchoidal fracture, and jet black colour, which fall under this heading, are usually classed as " asphaltites " in the literature of the subject. The chief varieties met with in commerce are Gilsonite, manjak, and Grahamite.

Gilsonite (or Uintaite) occurs in vertical veins of varying width in the interstices of rocks. These veins, which run almost parallel, often extend for miles, and are chiefly located in Utah. In some cases the main veins are joined by branch veins or " tributaries " entering at a sharp angle.

The walls of the rocks are invariably impregnated with Gilsonite, but to varying degrees, according to the porosity of the walls.

The Gilsonite is mined, or rather excavated by means of pick and shovel, and there is nothing worthy of special note about its collection.

It is, however, usually separated into two qualities, known as first and second grade respectively ; the former represents material mined from the middle of the vein, and the latter material from close to the walls.

Gilsonite has a specific gravity of 1·05 to 1·10, and a melting-point varying from 250° to 350° F. in different samples. It is almost completely soluble in carbon bisulphide, the natural mineral matter present being usually less than 1 per cent.

Manjak (or Glance Pitch) deposits are to be found in various regions, amongst which may be mentioned Mexico, West Indies, and Colombia.

While generally similar to Gilsonite, and having a melting-point of approximately the same order, it is much more friable and has a higher specific gravity, viz., 1·10 to 1·15.

Grahamite occurs chiefly in Texas, Oklahoma, and Cuba.

Its characteristics are less uniform than those of the asphaltites already referred to, several varieties, differing chiefly in mineral content (from practically *nil* to 50 per cent.), being often found in the same vein.

Naturally the lustre, fracture, and specific gravity vary accordingly. Normally the specific gravity varies from 1·15 to 1·20, but in samples containing a large proportion of mineral matter it may be as high as 1·5.

RUBBER

Wild Rubber.—Rubber-bearing trees are found growing wild in certain of the tropical and sub-tropical countries, forming a belt round the earth approximately 25° north and south of the equator.

There are several types of wild rubber, the variations between them being primarily botanical, and secondarily in methods of coagulation and preparation for the market, but the one with which the cable manufacturer is most concerned is that obtained from the *Hevea Brasiliensis* (Para rubber), a species indigenous in large tracts of South America, especially the areas adjacent to the Amazon and its tributaries. A description of the methods of obtaining rubber from this source should therefore suffice.

The rubber is obtained from the latex, a milky-white juice obtained by making excisions in the bark of the trees by means of a small axe, usually in the form of oblique lines or V-cuts. The exact function of this latex to the tree is not known, but it is a system distinct from the sap.

Small collecting cups are attached to the tree beneath the excisions for the purpose of catching the latex as it trickles out, and it is subsequently transferred to larger vessels in which it is conveyed to the smoking sheds. Here it is transferred to flat basins in readiness for the coagulation, which is carried out on the following lines. A fire is made, usually of palm-nuts, which produce a smoke rich in acetic acid, creosote, etc. The latex is poured over a thick stick or paddle supported at one end over the fire on a rough wooden framework, the other end being rotated by the operator. The heat from the fire results in the evaporation of the water, leaving behind a thin film of rubber; this operation is repeated over and over again, resulting in the building up of a ball of rubber, consisting of a multitude of thin layers, and weighing as a rule from 30 to 50 lb., sometimes larger. The ball is then cut longitudinally and stripped off the paddle and exported in this state.

The good keeping quality imparted to the rubber by this method of coagulation is probably due to the antiseptic properties of the acetic acid, creosote oil, and allied substances produced by burning the nuts; and it is worthy of note that other " brands " of rubber from other parts of South America and from the same botanical source but coagulated by chemical precipitation show quite opposite characteristics, decomposing readily in store or transit and being consequently of far less technical and intrinsic value.

Plantation Rubber.—Until a few years ago rubber was obtained exclusively from trees growing wild, but as supplies were not keeping pace with the ever-increasing demands, the possibility of cultivating rubber-bearing trees was considered. In 1875 the India Office commissioned Mr (now Sir Henry) Wickham to collect the seeds of the *Hevea Brasiliensis*; these were duly obtained and despatched to Kew Gardens. The following year about 2000 seedlings were sent out to Ceylon, planted, and reared; it was not, however, until some years later, in fact the beginning of the

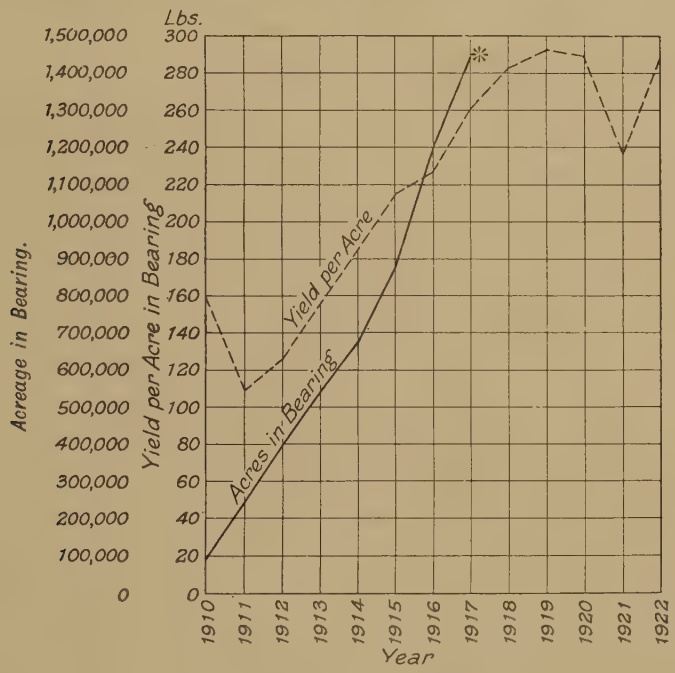

Fig. 6.—Plantation Rubber.

present century, that planting on a commercial basis began, and in the first decade the acreage under rubber in Ceylon increased approximately twenty-fold.

Planting was also commenced in Malaya, where the natural climatic and soil conditions proved so advantageous that rubber cultivation went ahead by leaps and bounds, until by 1923 an area of over two and a quarter million acres had been planted, of which approximately 75 per cent. was actually producing rubber; more than one-half of the total supply is at present obtained from this source. The above diagram † illustrates the rapid increase in planted area and average yield per acre in bearing.

The increase in the quantity of rubber contributed to the world's supply by the plantations, and the superior quality produced by the systematic and more or

* No census of planted area under British control taken since 1918.

† From data compiled by W. H. Rickinson & Son, London.

less scientific methods of growing and preparation for the market, have naturally resulted in medium and low-grade rubbers largely disappearing from use, in spite of the fact that many of them had special uses for which the high-grade Para rubber is less suitable. Economic considerations have become a more and more potent factor during the past few years, and at the present time the organised and standardised methods of the plantations are driving even the best medium wild rubbers off

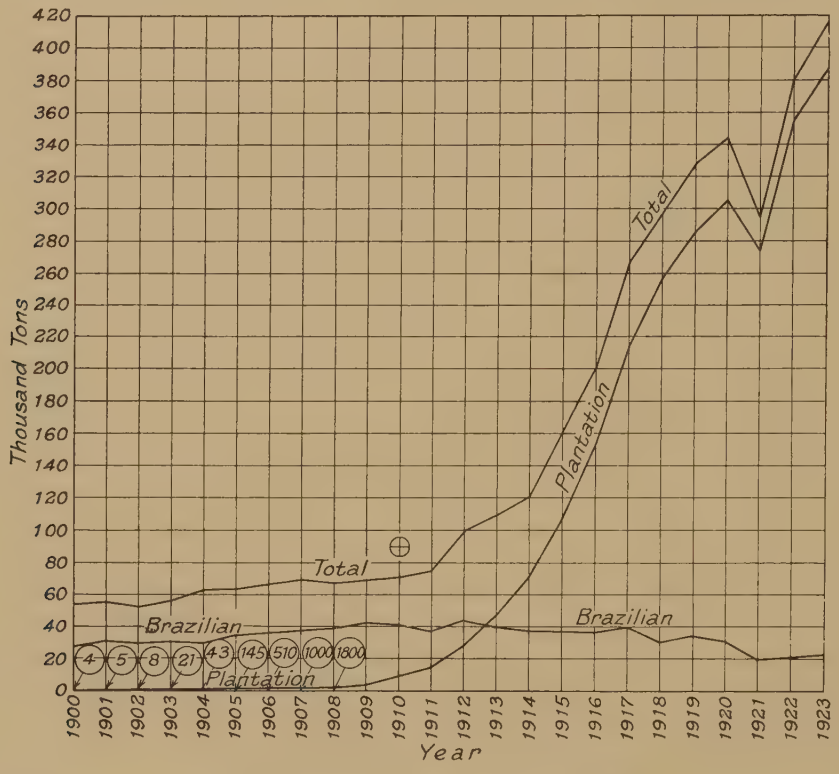

Fig. 7.—World's Production of Rubber.

the market on price alone. The above diagram shows how rapidly the plantation output has gained on the total supply.*

The table † shown on the opposite page gives the acreage under plantation rubber for the various countries.

Restriction of Supply.—The falling off in production shown in the diagram about the period 1920-21 coincides with the general industrial depression, and the political and financial disorganisation of European countries. This caused a slump in the demand for rubber which reacted disastrously on the market value. During

* One notable effect of this rapid expansion of plantation rubber production is that at the present time the British Empire owns approximately 70 per cent. of the world's rubber acreage.

† Data compiled by W. H. Rickinson & Son, London.

⊕ At this period Brazilian rubber (Hard Fine Para) reached the record price of 12s. 9d. per lb.

1922 plantation rubber reached the low figure of 6¾d. per lb., which meant that the producers were working under a heavy loss. A continuation of this state of affairs —unsatisfactory to producers, manufacturers, and all concerned—would certainly have ended in bankruptcy for many plantation companies with consequent

TABLE V

Percentage.	Country.	Plantation acreage during 1923.		Actual yield in 1923, per acre in bearing. lbs.
		Total planted acres.	In bearing acres.*	
56·8	Malaya .	2,230,000	1,672,500	264
10·5	Ceylon .	410,000	307,500	270
3·2	India . .	127,000	95,250	151
25·4	Dutch Indies	1,000,000	750,000	374
4·1	Rest . .	160,000	120,000	293
100·0	Total .	3,927,000	2,945,250	293†

deterioration of their properties. This would have been a very much more serious matter than might appear on the surface, because any relaxation of stringent estate management would leave the trees exposed to the ravages of disease.

It is therefore safe to assume that if some form of restriction had not been introduced many plantations would have been ruined. Apart from the wastage of capital entailed, the period required for new trees to come into bearing would have led to a disturbance of the relation between supply and demand when the latter again became normal, and this in turn would tend to cause prices to go to an artificially high level.

After a number of unsuccessful attempts to voluntarily restrict supplies a Committee was appointed with the following terms of reference—" To investigate and report upon the present Rubber Situation in British Colonies and Protectorates for the information of the Secretary of State for the Colonies, and to advise what remedial measures should be taken to improve the existing position."

Briefly, the following were the recommendations :—

As a basis of standard production the actual output of each producer during the twelve months, November 1919 to October 1920, was taken, and 60 per cent. of this production formed the basis of the scheme.

The pivotal price is fixed at 1s. 3d. per lb., and the percentage of " Standard production " regulated according to whether this figure is averaged over a period of three consecutive months. Thus if this figure is maintained the percentage of " Standard production " is automatically increased by 5 per cent. and so on ; conversely provision is made to reduce the percentage of " Standard production " by

* 75 per cent. of planted acreage. † Average yield per acre.

5 per cent. if the price does not average 1s. per lb., over a period of three consecutive months.

The Restriction Scheme has not been accepted by the Dutch producers, and the actual yield per acre in the Dutch Indies for the year 1923, as shown in the foregoing table, is significant, in comparison with the countries in which the arrangement operates.

The Stevenson Restriction Scheme (as it is known) came into operation on the 1st November 1922. The Scheme has been much criticised, but the fact remains that through its introduction world stocks have been considerably reduced, and the price up to a recent period, maintained an economic level.

The methods of collecting the latex in plantation practice differ from those employed in the Amazon forests. As regards the tapping, various systems and different forms of excision have been tried with the object of getting maximum yield without injuring the tree, this being naturally of much greater importance in the plantation than in the forest.

As a result of careful study and experiment the method now most generally adopted is known as the " half herring-bone." This consists of making an oblique cut extending about one-quarter of the circumference of the tree, the lower end of which is connected by a vertical channel cut to the base, down which the latex runs into a collecting cup. The first oblique cut is made fairly high up on the tree ; and succeeding cuts, which are usually done on alternate days, are made on the lower edge of the previous one. This process is continued until the end of the season, when the whole of the bark on this quarter of the tree has been removed.

Tapping operations are then commenced on the opposite quarter, and the two remaining quarters treated in succeeding years. This cycle of operations permits of continuous repetition, the bark of the first quarter being healed in time to commence tapping again.

The latex is strained through wire gauze or muslin to remove extraneous matter, and poured into shallow rectangular enamelled iron pans.

In the early days of plantation work numerous methods of coagulation were tried. One of the most interesting, from the point of view of the technical excellence of the product, was the smoking method. Many varieties of this method were proposed, the most successful being based on the principle of forcing smoke through the latex. By comparison with the simple addition of acetic acid, however, these methods were slow, laborious, and expensive; and to-day the acetic acid method holds the field, having in course of time been reduced to an exact process producing satisfactorily uniform results. The smallest quantity necessary to effect coagulation is added, and the latex allowed to stand a sufficient length of time for the globules of rubber to coalesce, leaving the residual liquid quite clear and free from rubber.

The clot of rubber thus formed is removed and allowed to stand overnight ; it is then macerated, washed, and sheeted in a machine of the type illustrated in Fig. 8. This machine bears a general similarity to those used in the rubber factory (for washing wild rubbers), which will be described later. On account of the soft

character of the rubber at this stage and the importance of turning out the finished sheet in uniform thickness the parallel adjustment of the rollers is accomplished by the worm-wheel gear shown in the illustration instead of by independently screwing up each end of the adjustable roller as in the ordinary washing machine.

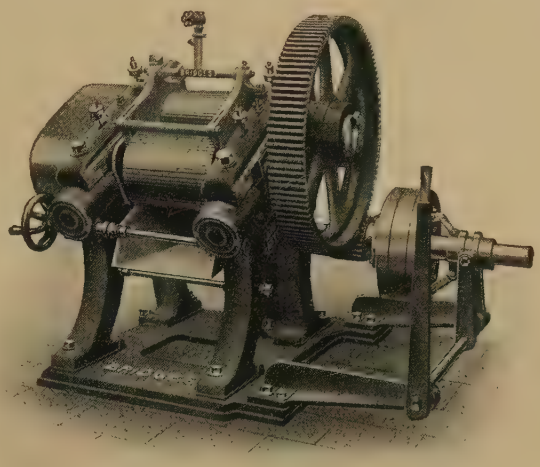

Fig. 8.—Macerating and Crêpeing Machine.

The sheets are now taken to the drying sheds and placed on racks, the temperature of these sheds being maintained at 70° to 100° F.

In the case of smoked rubbers the drying and smoking operations are combined; the smoke is either generated from a furnace outside the shed and driven through in conjunction with a current of air, or it may be produced on the ground immediately below the sheets of rubber. After it has been subjected to the above operations the rubber is pressed, packed into cases, and is then ready for export.

Plantation rubber produced on the foregoing lines closely resembles, but hardly equals—so far as certain technical results are concerned—the Hard Fine Para rubber produced by the natives in South America.

The plantation product, however, has improved appreciably in recent years, as indicated by the fact that whereas the market value of Hard Fine Para rubber (which is naturally the criterion of the manufacturer's technical valuation) was, until recently, always a few pence per lb. higher than the best plantation rubber, it is now approximately the same. There is still a difference, however, when the loss in weight caused by washing and drying (the preliminary manufacturing operation) is taken into account, namely, 15 to 17 per cent. in the case of Para, and an average of only ·7 per cent. for Plantation rubber.

So far as cable manufacture is concerned, although some manufacturers had employed it in their standard goods for several years, it was not until a late stage of the war was reached that the British Admiralty and War Office standard specifications were relaxed to permit the use of plantation rubber in place of the Brazilian Hard Fine Para that had always previously been specified. By that time, however, the best standard grades of plantation rubber had reached such a stage of excellence that little difficulty was encountered in fulfilling the rather stringent electrical and physical requirements of the specifications.

For many purposes selected plantation rubber sheets may be used without

washing, but for cable insulation purposes this operation should on no account be omitted. Although the risk of mechanical impurities (which would cause insulation faults) may be small, and variations in surface condition (traces of mould, etc.) may be obvious on inspection, the ultimate electrical tests on the finished cable are such a delicate criterion of excellence that nothing short of absolute purity, cleanliness, and uniformity should be aimed at.

Compounding Ingredients.—Compounding ingredients used in the rubber mixings may be roughly classified as follows :—

Class	(*a*)	Fillers.
,,	(*b*)	Accelerators of vulcanisation.
,,	(*c*)	Pigments.

This classification is not absolutely definite. For instance, some materials commonly used under Class (*a*) as " fillers " are not without effect as accelerators of vulcanisation and are also excellent pigments, and so on. In fact, every ingredient has some more or less pronounced and characteristic influence on the ultimate product. Generally speaking, however, it may be taken that sulphur is the chief—and, for the purpose under consideration, the only—vulcanising agent used ; that its combination with rubber (and, there is reason to believe, its method of combination) is accelerated and controlled by certain mineral substances, such as litharge and magnesia and by various organic materials usually sold under various trade names ; and that various grades or qualities of vulcanised rubber may be produced by adding more or less inert filling (mineral) materials, such as French chalk, zinc oxide, whiting, and lithopone, and coloured by pigments such as carbon black, antimony sulphide, chromic oxide, ultramarine, etc. A much greater range of compounding ingredients is used in general rubber manufacture, but for cable insulation purposes they are more or less confined to those mentioned above.

While standard British specifications for cable rubbers usually preclude the use of any organic substance but rubber in a vulcanised rubber compound, a small percentage of wax (usually cerasin or paraffin) or of a pure bituminous material of the type known as mineral rubber, is often used for special technical reasons of manufacture, as mentioned later.

This is not objected to as a rule because it exists in such small proportion as to preclude any suspicion of adulteration or fraud, the chief object of the said prohibition being to prevent the use of " reclaimed " rubber and rubber " substitutes." It may be here noted that so far as high-grade cable rubber compounds are concerned, practically all inducement to use the last-named substances has been removed by the low values to which the rapidly expanding supply has brought raw rubbers.

It is essential that all the vulcanising, accelerating, filling and colouring substances above mentioned should be in as finely divided a state and of as fine a texture as possible. They should leave no appreciable residue on a sieve having 90 meshes to the inch, and should be practically free from moisture.

The following notes deal chiefly with the chemical properties and necessary degrees of purity, etc., of the foregoing substances.

The sulphur used in rubber mixings is usually in the form known as Flowers of Sulphur, and chiefly comes from Sicily. It is a fine powder produced by sublimation. It should contain no trace of free sulphuric acid, and the ash is usually determined with a view to detecting mineral adulterations or contaminations. " Precipitated " sulphur is perhaps the best form, on account of its impalpable amorphous state, but as its advantages chiefly relate to admixtures with pure rubber (in which, for cable purposes, it is not used) its high cost is not justified.

French chalk, also known as talc, is a hydrated magnesium silicate. It is a filler pure and simple, being quite inert and having no action on the rubber and taking no active part in the vulcanisation process. It has a very appreciable influence on the insulating properties of the rubber compound, and for this reason finds a place in practically all vulcanised cable rubbers. French chalk is graded commercially according to its colour ; the degree of unctuousness should also be taken into consideration. A water extract invariably shows slight alkalinity, but it should be free from effervescence (indicating presence of carbonates) when treated with dilute acid. A further check on the presence of carbonates as adulterants is the ignition loss, which in a normal sample is about 6 per cent. The specific gravity of French chalk is approximately 2·7.

Zinc oxide, in addition to fulfilling the part of a filler, is also regarded as a white pigment. It also has a toughening effect on rubber, and tends to increase its durability. It should be almost chemically pure, completely soluble in dilute acetic acid, and free from iron, copper, and lead. The specific gravity of zinc oxide is approximately 5·5.

Formerly the terms zinc oxide and zinc white were synonymous, but in view of the fact that other white pigments having zinc compounds as their basis (and more properly classed as zinc whites) have been used largely in latter years, it is customary to reserve the latter term for these compounds, to distinguish them from the pure zinc oxide. The predominating constituent of these zinc whites is barium sulphate, together with variable proportions of zinc sulphide and oxide. Such compounds are Orr's zinc white, lithopone etc.

Briefly, they are mixtures in molecular proportions of barium sulphate and zinc sulphide, obtained by precipitation on mixing certain barium and zinc salts. The composition, which of course depends on the details of the process, is variable, and an appreciable proportion of zinc oxide (6 to 12 per cent.) is often present. The barium sulphate content is usually in the neighbourhood of 70 per cent., the zinc sulphide 16 to 22 per cent., and silica, iron, and alumina, etc., $1\frac{1}{2}$ to 2 per cent.

The method of preparation ensures that the constituents are in a far more intimate state of admixture than would be attainable if they were merely mixed together in the dry state. At best, however, these zinc whites can only be regarded —for cable rubber purposes—as a cheap substitute for zinc oxide. Rubber compounds in which they are so used have their insulation resistance reduced in consequence, although not to an extent necessarily detrimental to the durability of the dielectric, because in compounds of the usual type the total proportion will not be great. The reason of this effect on insulation resistance is somewhat obscure, but the fact

that the Admiralty and War Office specifications for cable rubber compounds prohibit the use of barium salts therein—although the exact reason for the prohibition appears to be lost in the mists of antiquity—may have some significance in this regard. It is within the author's experience, however, that a compound in which about 20 per cent. of barytes (barium sulphate) was accidentally used in place of another ingredient gave incredibly low insulation values. It may be mentioned that towards the end of the war the embargo above referred to was (ostensibly) removed by permission being granted to use zinc white in lieu of zinc oxide, on account of shortage of the latter.

With regard to testing zinc whites for use in rubber compounds it is usually sufficient to estimate the acid insoluble matter, sulphide, and moisture.

Whiting consists chiefly of calcium carbonate. It possesses no specially advantageous properties and is chiefly used in cheap mixings. It should be practically all soluble in dilute hydrochloric acid, should leave only undissolved a small quantity of silica, and contain only traces of iron or alumina. The specific gravity is approximately 2·6 to 2·8.

Litharge (PbO) as used in rubber manufacture is prepared in two varieties, the first of a brownish red or orange colour and the second of a bright canary yellow. The former type is made by the oxidation of lead in special furnaces ; the molten litharge is run out into moulds, and on cooling breaks up into flakes and is subsequently ground up into a powder. It remains, however, more or less flaky, which militates against its uniform dissemination throughout the rubber ; and from the nature of the process it is liable to contain metallic lead on the one hand, or on the other traces of peroxide of lead. The second variety was up to a few years ago made in Germany (although originally produced in England) by means of a patent mechanical process ; latterly, however, a well-known firm in England have been manufacturing this kind, which has the advantage of being in finely powdered form, and are now producing material of a superior quality.

Litharge should be practically all soluble in dilute acetic acid, and should be free from particles of unchanged metallic lead, lead peroxide, and copper salts, both the latter being prejudicial to rubber. In addition to possessing the property of accelerating vulcanisation, litharge has also considerable pigmentary power. This is due to the formation of (black) lead sulphide during vulcanisation.

The specific gravity of litharge is approximately 9·3 to 9·5.

Magnesia (MgO), also known on the Continent as magnesia usta, should be almost pure magnesium oxide. There are two varieties, namely, " light " and " heavy " ; the former type appears to produce the more satisfactory results. Magnesia possesess the advantage over litharge as an accelerator that it does not produce any change of colour during vulcanisation and is therefore available for use in white or drab rubbers. It can, however, only be used in very small proportion in cable compounds because it seriously lowers the insulation resistance of the dielectric (the effect of introducing even 0·5 per cent. being quite marked), although in common with other accelerators it improves the mechanical properties and durability of the rubber.

It should not contain more than small quantities of carbon dioxide, calcium, or

silica ; the ignition loss should not be more than 2 per cent. ; although in cases where the magnesia has been exposed to the atmosphere it may be as high as 20 per cent., due to absorption of carbon dioxide and moisture. On account of this tendency it should be stored in tightly closed bins.

The apparent gravity is also useful in indicating to a certain extent the texture of the material. It is found by introducing the powder into a graduated flask and then tapping the flask on a table or bench until the surface of the powder is coincident with the mark on the neck of the flask. The tapping is continued (more powder being added if necessary) until there is practically no diminution in the volume. It is then weighed, and knowing the weight of an equal volume of water, the apparent gravity may be obtained. This is quite an arbitrary figure, but is useful for the comparison of different consignments.

Organic accelerators, and the mineral accelerators already described, differ essentially in the manner in which they promote the accelerating action. The addition of such a small quantity as 0·5 per cent. of some examples of the former type is sufficient to reduce the time of vulcanisation to about one-third of that normally required, and in view of the small quantity used, it is generally concluded that the action is of a catalytic nature.

In the case of mineral accelerators, however, various theories have been put forward to explain the action, such as the generation of heat due to chemical interaction of the basic oxides and part of the sulphur present, which facilitates the reaction between the molecules of rubber and sulphur, and thus increases the rate of vulcanisation.

While it is certain that such interaction does occur (causing the formation of sulphides and sulphates), and that heat must be generated in the formation of these inorganic compounds, it also seems certain that such theories do not tell the whole story. An interesting sidelight—which, however, in the present state of our knowledge of the chemistry of vulcanisation seems only to accentuate the darkness—is furnished by electrical tests which show that whereas one basic oxide, *e.g.*, magnesium oxide, may have even a greater effect in reducing the insulation resistance of a given rubber compound than an equal proportion (say, 0·5 per cent.) of an organic accelerator, another basic oxide, for example, litharge, may be used up to 5 or 6 per cent. without showing a similar effect. Such differences are not proportional to the " heats of formation " of the substances concerned ; and, moreover, different behaviour with regard to absorption of moisture (as evidenced by insulation resistance measurements after various periods of immersion in water) rather tend to indicate differences in molecular structure, and consequently in the " mechanism " of the vulcanisation reaction.

These facts, to which the author has previously drawn attention,* are mentioned with the object of indicating that electrical tests constitute a valuable weapon in the armoury of the investigator of matters pertaining to the vulcanisation of rubber.

The first organic accelerator to be used on a commercial scale was piperidine,

* Beaver " Cables," *Jour. I.E.E.* vol. 53, p. 69, 1914.

and the use of this product was patented by Messrs Bayer & Co., of Germany, in 1912. Later, a solid derivative of piperidine having similar properties was produced, and this substance appeared on the English market early in 1914.

About the same time an English chemist (Peachey) discovered that certain other organic compounds possessed the property of accelerating vulcanisation, amongst which were the nitroso derivatives of certain bases, such as dimethylaniline, methylaniline, and diphenylamine.* Paranitroso-dimethylaniline has been sold under the name of " Accelerene " for some years past, and has given very satisfactory results in cable manufacture.

Aniline is stated to have been used in the United States about 1906 for the purpose of increasing the rate of vulcanisation, but it is only since 1914 that intensive research has been carried out in this direction.

The following are a few of the more common synthetic organic chemicals used as accelerators in the rubber industry :—

Paranitroso-dimethylaniline.
Diphenylguanidine.
Triphenylguanidine.
Thiocarbanilide. (Diphenylthiourea.)
Aldehyde Ammonia.
Hexamethylenetetramine.
Aniline.
Paraphenylenediamine.

In addition to the above there are the " super " or " ultra " accelerators, such as certain of the dithiocarbamates and the xanthates, which are of more recent introduction, and which require an " activator " such as zinc oxide.

The choice of accelerator depends on the desired character of the product, and on the method of vulcanisation. For example, certain accelerators produce better results in closed moulds than in the open steam cure.

Of the many theories that have been propounded as to the action of organic accelerators, probably the most widely supported is that an active nitrogen group is split off, and that a reaction product therewith of sulphur constitutes the catalytic agent.

It is generally stated that the principal advantage of organic over inorganic accelerators is the reduction in time of vulcanisation required to attain " optimum " cure. In ordinary rubber manufacture this is to a large extent true ; but in cable manufacture the improvement in physical and chemical properties (the latter including resistance to deterioration and reduced action of sulphur on the tinned copper conductor) is of still greater importance.

Comparisons made by the author on samples kept side by side for eight years leave no doubt as to the superior " ageing " properties of vulcanised rubber compounds containing organic accelerators.

It is interesting to note that one result of the comparisons referred to was to

* Patent No. 4263/1914.

show that the superiority was not due so much to the lower degree of depolymerisation of the uncombined rubber consequent upon shorter exposure to the heat of curing, as to the specific curing effect of the accelerator, the samples being fairly heavily compounded, and the correct curing conditions not appreciably different.

There seems little doubt that the " anti-oxidant " character of some of the organic accelerators explains the improved ageing qualities which are attained by their use.

The identification and examination of organic accelerators calls for chemical knowledge of a high order, owing to their complex composition, and it is of the greatest importance that the nature of the substance and degree of purity should be known.

Owing to the great variety, it is not possible to formulate a scheme of analysis which would include all the substances used, and published data on these lines is very scarce.

The most comprehensive contribution yet published appeared in the *Transactions of the J.S.C.I.*, vol. xliii., No. 1, " The Analysis of Organic Rubber Vulcanising Accelerators," by Callan and Strafford, and the reader is referred to this article for further details.

In rubber mixings there is invariably a larger quantity of sulphur than is theoretically required to combine with the rubber during vulcanisation, and this excess is known as " free sulphur."

It is diffused throughout the mass in minute globules, but subsequently crystallises, and, in accordance with the well-known laws governing the movement of crystalloid substances in colloidal bodies, tends to move to the surface, causing the phenomenon known to rubber manufacturers as " blooming " or " sulphuring-up."

By the addition of a suitable accelerator, however, the quantity of sulphur added to the mixing may be considerably reduced, inasmuch as the catalyst tends to bring about the more complete combination of the rubber and sulphur. The same result, it may be noted, is to a large extent attained by the use of the mineral accelerators, the free sulphur being reduced in quantity by its combination with the basic oxides, forming, as previously mentioned, sulphides and sulphates.

With regard to waxy and bituminous ingredients in cable rubber compounds—previously referred to as admissible in small proportions—the use of the former, although by no means unknown in the manufacture of certain rubber goods, was first introduced into cable rubber compounds by the author some twenty years ago with the object of counteracting the natural adhesiveness of freshly calendered rubber compound sheets, and obviating the previous practice (which was objectionable from many points of view, and involved risks in subsequent manufacturing operations) of shellac varnishing one surface of the sheet as it left the calender. Naturally, no more than a sufficient proportion of wax for this purpose is desirable, otherwise the degree of adhesiveness required by subsequent cable-making operations tends to be nullified, and so it comes about that the proportion is automatically limited to about 2 per cent. In the finished goods the presence of wax is beneficial, tending to preserve the vulcanised rubber from deterioration.

A high grade of " spirit refined " paraffin wax is generally used, having a

melting-point of 130° to 132° F. Freedom from sulphur, although not a technical necessity from the point of view of the use to which the wax is to be put, is a fair criterion of its degree of purity as well as of the method of refinement. A simple test for sulphur is to immerse a piece of bright copper wire in the molten wax for an hour. In presence of traces of sulphur it will be tarnished, but will remain bright if sulphur is absent.

The use of cerasin, which is expensive and difficult to obtain pure and free from resin—an objectionable impurity in a rubber compound—offers little or no advantage over pure paraffin wax for the purpose.

With regard to bituminous materials, certain native bitumens—of the Gilsonite type—found chiefly in Utah, U.S.A., have been largely used in ordinary rubber manufacture during the past few years. They are practically free from mineral matter, and have a low sulphur content. They usually have high softening points and break with a conchoidal fracture. In spite of this apparently great physical disparity these " mineral rubbers," as they are termed, are readily blended with rubber on the mixing rollers. They combine with sulphur in the vulcanisation process, and their chemical properties undergo changes comparable with those which occur in the rubber itself, these facts being demonstrable by chemical analysis.*

The admixture of bitumen of this type with rubber has a beneficial effect on it as regards preservation from atmospheric and other forms of chemical attack.

It also tends to prevent " blooming " (above referred to), primarily because, like the inorganic accelerators and basic oxides, it combines with sulphur, which might otherwise be " free," or in other words it improves the " coefficient of vulcanisation " (see under Design, p. 180), and partly because of the homogeneous structure of the mixture.

The admixture has a marked effect in reducing the resilience and elasticity of the rubber, but on the other hand makes it tough.

This physical characteristic eminently fits it for extrusion methods of cable covering, but militates against the attainment of " stretching test " results specified in British Government and other specifications. The permissible proportion in which it can be actually used in British practice is therefore much below that at which it could be regarded as a rubber substitute. It is in fact little used except in " tough rubber " sheaths, which are formed by extrusion methods, and in certain special types of dielectric referred to in Chap. I (p. 21).

Special colouring substances are not often required in cable rubber compounds, the chief notable exception in present day practice being that earth cores in tough rubber sheathed portable or trailing cables are usually distinguished by a red rubber covering. (Distinction in other types of cable is usually attained by colouring the fibrous coverings which are applied over—or in some cases under—the rubber dielectric.) The best pigment for this particular purpose is Antimony Sulphide, otherwise known as Golden Sulphide or Antimony Sulphuret. It produces that characteristic orange red colour with which the best red rubber goods are generally associated. In ordinary rubber manufacture red rubbers are also produced by the

* Caspari, *India Rubber Laboratory Practice*, Macmillan & Co., 1914.

use of such pigments as cinnabar (sulphide of mercury) or iron oxide (usually the peroxide or the hydrated oxide); the former, however, gives a colour which is unnecessarily brilliant for the simple purpose of distinction, and is, moreover, very expensive; and the latter, while being much cheaper than antimony sulphide, produces a less durable vulcanised rubber.

There are several varieties of antimony sulphide, the colours ranging from crimson to orange and containing varying proportions of antimony sulphide, free sulphur, calcium sulphate, etc., according to the mode of preparation.

Antimony sulphide was at one time regarded as a vulcanising agent, but the action was no doubt due to the free sulphur invariably present, which ranged from 7 to 20 per cent., according to the variety: the sulphide itself, however, acts to some extent as an accelerator. Latterly, an English brand of the crimson variety has been put on the market, which contains only 0 to 3 per cent. free sulphur. It is essential that the amount of free sulphur should be known in order that it may be allowed for if appreciable. It may be estimated by extracting a weighed quantity in a Soxhlet apparatus for about ten hours with carbon disulphide. The solvent is then evaporated, the extract dried for about one hour at 140° F., and subsequently weighed. The varieties containing calcium sulphate naturally contain a correspondingly smaller quantity of antimony sulphide, and are consequently cheaper. For red rubber compounds for insulating purposes the so-called "crimson" variety is usually used; it should contain no calcium sulphate, and the minimum quantity of free sulphur.

It may be mentioned that instead of using pigments mixed with the rubber, it is quite feasible to dye an ordinary white insulating rubber compound after vulcanisation by the use of certain red dyes which for some obscure physico-chemical reason (probably depending on the colloidal form of the dye and its relation to that of the rubber) penetrate vulcanised rubber at a phenomenal rate. These particular dyes are soluble in paraffin and other waxes, which serve as a vehicle for the dye stuff, and the vulcanised rubber-insulated cable only needs to be immersed in the coloured wax for a few seconds at a temperature of about 200° F. The affinity of the vulcanised rubber for the dye is such that after this preliminary introduction of the dye to the outer surface of the rubber, the penetration proceeds in the cold, quickly tinting the complete cross section of the dielectric, and continuing to increase in depth of colour for many days until apparently a state of equilibrium is reached.

In connection with this phenomenon it may be worthy of note that the particular dyes referred to are more brilliant in colour and faster to light, etc., than other dyes used for similar purposes. There appears, however, to be no determinable difference in chemical composition, and it therefore appears reasonable to suppose that the fundamental difference is physical, and dependent on methods of manufacture of the dyes. It may be added that neither the physical conditions of the rubber nor its electrical characteristics are appreciably affected by this treatment.

Carbon black, commonly called lamp-black, is practically the only colouring matter available for producing black rubber, although, as previously stated, the

partial conversion of litharge into lead sulphide during vulcanisation causes blackening. As, however, litharge is only used as an accelerator of vulcanisation in a rubber mixing of the type generally employed for cable-insulating purposes, and is therefore in small proportion compared with the white compounding ingredients, the colour resulting from it is grey rather than black, and a small percentage of carbon black is usually added—even when litharge is used—to produce a definite black colour.

As the common term " lamp-black " indicates, it is made by condensing smoke on cold metal plates, etc. When made from oils, *e.g.*, tar oils, resin oils, and fish oils, it is called " vegetable " black—a term which could be used more correctly for another type of black, made by burning certain woody matter. The former is very liable to contain traces of oily matter owing to imperfect combustion of the oils, and as these are deleterious to rubber the proportion in which they exist should be determined by extracting a sample of the material with ether for several hours, subsequently evaporating off the ether and weighing the residue. In a good make of this type of lamp-black the ether soluble matter should not exceed 0·7 per cent. It should be practically free from mineral matter, and also from gritty matter, which is sometimes found on the poorer qualities in the form of small particles of coke. The type of lamp-black referred to above as being produced from woody matter is chiefly produced in Sweden as a by-product of the wood-pulp industry, both tree barks and pulp residues being utilised. Although sold in this country as lamp-black and having uses in other industries, the latter type is not very suitable for rubber work and should never be used in cable rubbers, because being practically powdered charcoal it cannot be made to approach the fine degree of subdivision required for this purpose.

From this point of view the best type of carbon black is made in America from the combustion of natural gas, and this ensures, firstly, that it is in the finest possible state of division, and, secondly, that it is free from oily and mineral matter. The former advantage is claimed to be so great that this type of black can be effectively used as an ordinary compounding ingredient (to the extent of 10 to 20 per cent.) as distinct from a mere colourant (for which purpose it would only be used to the extent of less than 1 per cent.), and it is stated that its advantages over the ordinary " fillers " have been very definitely proved by extensive road tests on solid and pneumatic tyres.

In addition to claims as to increased strength, resilience, durability, and lower specific gravity in compound rubbers in which a proportion of the ordinary mineral ingredients, such as zinc oxide or lithopone, is replaced by this carbon " gas " black, it is stated that vulcanisation is effected in an appreciably shorter time. According to tests made by the author, there would appear to be a substantial foundation for these claims.

In rare cases, such as in British War Office specifications for certain types of cables for submarine mining work, coloured rubbers such as green, blue, and yellow (other than the commonly used black, white, and red rubbers above referred to), are called for, probably because under the action of sea-water, colour distinctions

applied to fibrous coverings are liable to be nullified in course of time. As in the extended use of electric cables in the future similar requirements may occur, brief reference will here be made to the available colouring substances.

The best and most reliable green pigment is chromic oxide, provided always that it is pure and free from adulteration, especially with other green pigments containing copper and arsenic, which are highly inimical to rubber.

The safest blue pigment is ultramarine.

As regards yellow pigments, pure cadmium sulphide is the most reliable. Like antimony sulphide, it appears to act as an accelerator of vulcanisation.

In view of the comparative unimportance of the matter of cost of these pigments, *i.e.* on account of the rarity of their employment, the small proportion used in the rubber compound, and the low percentage relation of their value to that of the finished cable, it is unnecessary to consider the comparative merits of other—less reliable—pigments.

In concluding these notes on compounding ingredients, attention may be drawn to further remarks under DESIGN—Dielectrics—page 176, regarding the physical effects of their admixture with rubber. This aspect of rubber manufacture is worthy of closer study (especially in conjunction with vulcanisation effects) than it has apparently hitherto received.

VULCANISED BITUMEN

As is well known, certain kinds of bitumen become appreciably toughened and hardened by heating with sulphur in a manner analogous to the vulcanisation of rubber; in fact some of them give excellent technical results in admixture with vulcanised rubber compound.

As noted in Chap. I (p. 21), however, it was found in the early days of electric light and power cables that pure refined bitumen used alone in this way did not possess sufficiently good mechanical properties for average purposes and conditions of use, and the composition was subsequently modified in order to overcome the deficiencies of the original material. This modification consists chiefly in the addition of certain products of the distillation of vegetable oils, which in the vulcanisation process undergo chemical changes of a similar character to those mentioned above, but produce very much improved physical results.

The methods of manufacturing vulcanised bitumen, up to the stage of preparing it for application to conductors, vary with the practice of different makers, some of whom prefer to melt and mix the ingredients, pour the mixture into moulds, and apply the heat treatment necessary to bring about the vulcanising reaction to the exterior of the moulds.

The author prefers—for the sake of thorough mixing and uniform heating—to employ a mixer of the type shown in Fig. 9, in which the ingredients are first reduced to the molten state and blended together, and the sulphur subsequently added after diluting it with an inert powder such as French chalk, in order to get

it well disseminated in the mass before the vulcanising reaction commences. By this process not only is the greatest general uniformity obtained, but the progress of the vulcanising reaction may be watched and arrested at the right time.

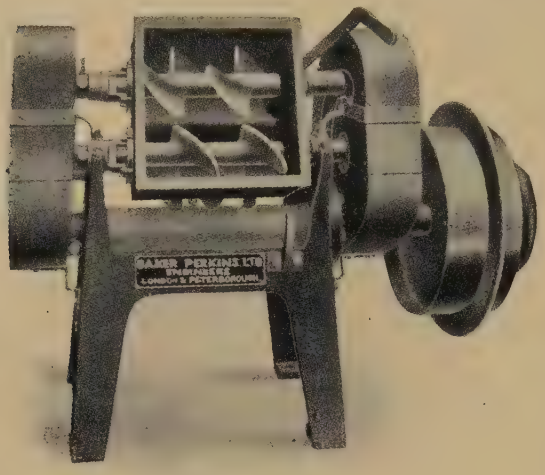

FIG. 9.—KNEADING AND MIXING MACHINE.

During the operation the material changes from a viscous liquid state to a heavily plastic condition, and when this change has proceeded far enough the mass is turned out of the machine to cool, after which it is "batched" up in thick sheets in an ordinary mixing machine as used for rubber mixing. After vulcanisation it is no longer meltable by the action of heat, and can only be manipulated by similar methods to those employed for rubber.

Its physical properties are perhaps best described by the following extract from the author's paper on "Cables" (*l.c.*, *ante*) :—

"The general idea of the physical properties of vulcanised bitumen that the average user of vulcanised bitumen cables probably has in mind is a general similarity to rubber, without any very specific appreciation of the limitations of that resemblance. It is very desirable from both maker's and user's points of view that such general ideas should be ventilated.

"To regard the matter first in a broad way, it may be said that the cohesion between the particles of material is much less in vulcanised bitumen than in rubber. This means that such properties as resilience, elasticity, and resistance to tension, compression, and other mechanical stresses have considerably lower values in vulcanised bitumen than in rubber. The differences may fairly accurately be considered as differences of degree. For instance, if rubber is masticated and its temperature thereby raised, its 'nerve' structure is broken down and it loses the above-mentioned properties to some extent. In this state its physical properties may be regarded as being 'slowed down,' as it were, to something roughly comparable with those of vulcanised bitumen at normal or medium temperatures.

"To turn from this broadly comparative aspect to a more detailed consideration of the physical properties of vulcanised bitumen, the variation in consistency with a change of temperature has probably the most direct bearing on the subject from the cable user's point of view.

"At very low temperatures (around or below the freezing-point of water) it tends to yield to sudden shock in a brittle fashion, breaking with a conchoidal fracture.

At medium temperatures up to, say, 100° F., it is a toughly plastic body having considerable resilience and resistance to mechanical stress. At temperatures in the neighbourhood of 100° F. to 130° F. it begins to lose its toughness, and at still higher temperatures its cohesion disappears to a considerable extent, although its resilience appears to be increased.

" As a result of this its manner of yielding to mechanical forces at very high temperatures bears a general resemblance to that of gelatinous materials and has no parallel in the behaviour of rubber. It does not yield by softening or by any process resembling the melting of bituminous, waxy, or resinous substances.

" It will of course be understood that in any material of this character the rate at which a given kind of stress is applied has a great effect on the result. It will also be appreciated that manufactured material of this kind may be varied in consistency either accidentally or intentionally, thereby causing variations in physical properties in relation to a given temperature range. For instance, a compound which is moderately soft at medium temperatures will give comparative freedom from brittleness at low temperatures under normally applied bending stresses, but will show marked brittleness under the same temperature conditions when the bending stress is suddenly applied, *i.e.* approximating to the sudden shock above mentioned. This characteristic and methods of determining its values is referred to in Vol. II under ' Testing.' At slightly elevated temperatures, initial softness is not an advantage, toughness being the most desirable property. On the other hand, hardness *qua* hardness has the general effect of raising the temperature range to a higher position in the thermometric scale, rendering it rather unsuitable for low temperatures. A material, intermediate as regards softness or hardness, possessing maximum toughness at medium temperatures, wide limits of temperature range, and approximately equal resistance to all kinds of stress at a low temperature, is obviously the most desirable."

A further extract from the same paper may be quoted on the subject of the chemical properties of vulcanised bitumen :—

" With regard to chemical properties the stability of vulcanised bitumen is remarkable. Unlike rubber, it is not appreciably subject to natural deterioration under normal conditions of atmosphere and temperature, and it may therefore be regarded as comparable with paper insulation in that causes of deterioration are practically always extraneous causes. So far as direct chemical attacks which may be encountered in practice are concerned, the material is exceptionally inert to the action of substances of an acid character. In fact, the author has for many years utilised vulcanised bitumen for the protection of other materials used in cable manufacture, such as lead, copper, rubber, and steel, from acid and oxidising influences.

" As might be expected from the fact that vulcanised fatty pitches, *i.e.* saponifiable substances, largely enter into the composition of vulcanised bitumen, it is much more susceptible to the action of alkaline substances. The direct action of such substances is usually, however, only superficial (to a greater or less extent depending on the degree of free alkalinity), and it is a fact that even such severe conditions as continual exposure to coal-pit waters—which are usually of an alkaline character—have had no appreciable effect on vulcanised bitumen. Even if such waters contain

free alkali equivalent to 25 to 30 grains per gallon (estimated as sodium carbonate), which is considerably above the average for waters encountered in coal mines in this country, and the vulcanised bitumen is freely exposed to their attack for two or three years, the depth of penetration of the action is inappreciable. Waters of a brackish character, which sometimes occur in coal mines near the sea and elsewhere, and which may contain 1000 to 1300 grains per gallon of the chlorides of sodium and magnesium, have no action on vulcanised bitumen."

VARNISHED CAMBRIC

Varnished cambric, also known as varnished cloth, " Empire cloth," varnished muslin, insulating cloth, etc., is a woven fabric usually of cotton, which is impregnated and coated with varnish. The " count " of cotton used in the fabric and its " weave " are varied according to the thickness (which is usually from 3 to 10 mils), flexibility, and other requirements of the finished material. In the small thicknesses, fine yarns of Sea Island cotton are sometimes used. For delicate purposes such as lapping on instrument wires and small flexibles, silk fabrics are sometimes employed, while on the other hand, where requirements of strength predominate, linen may be used.

The varnish should be composed of pure boiled linseed oil in which the only admixture should be one or more of the high-grade gum resins and a suitable quantity of " driers." Common resin (colophony) should not be used, although the mention of " resin " in books of reference in connection with general descriptions of the varnish indicate that it is, at any rate, sometimes so employed; as also does the type of decomposition of the varnish, which is sometimes found to occur in the course of a few years (even when kept at ordinary temperatures in a normal atmosphere), viz., a breakdown of the flexible surface film structure and its partial absorption by the fabric accompanied by change to a sticky consistency and the development of strongly acid characteristics.

In this connection, the author has observed that black varnished samples are usually appreciably less liable to such decomposition than the natural (yellow) coloured variety, and as this comparison applies to the same make—though observed in the products of more than one maker—it probably means that the bituminous matter used to produce the black colour is less harmful than some other ingredient, such as resin, used in the uncoloured varnishes. From the chemical aspect there would appear to be little reason to anticipate such deterioration provided that high-grade, pure boiled linseed oil, and suitable gum resins and driers, are used in correct proportions. It is, of course, well known that certain conditions in the actual process of varnish-making—apart from questions of composition—have great influence on the technical excellence of the varnish.

The pure linseed oil consists of the glycerides of certain fatty acids of the linolic and linolenic series, although variations in extraction and refinement processes may entail the presence of other glycerides, (which may to some extent affect the drying

and other properties of the oil) or even of free fatty acids. Such impurities will be guarded against by makers of the highest grade varnished cloths because they may cause variations in the process of oxidation by which the varnish films arrive at the final fully oxidised state which should be attained in order to get maximum chemical stability.

The fully oxidised body, known as linoxyn, is a neutral, insoluble, solid but flexible material, of remarkable stability under all ordinary conditions *—much more stable in fact than in the intermediate stages of oxidation, and for this reason the varnish should be given every facility for completely attaining the linoxyn stage (not merely superficially but throughout its mass) before the varnished fabric is put into use.

In the manufacture of varnished cambric it is of considerable importance that the cloth should have a smooth surface and be free from " nap " or stray protruding

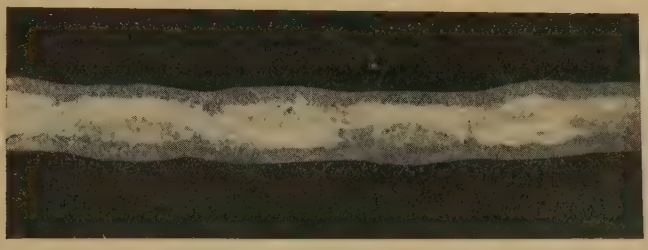

Fig. 10.—Photomicrograph of Varnished Cambric Section.
(Magnification × 50.)

fibres which might penetrate the films of varnish and form capillary communicating channels between the enclosed fabric and the atmosphere. To this end it is submitted to cloth " finishing " processes, such as firing and scouring, sizing, etc., and finally calendered.

In effect, the cloth is little else than a carrier for the varnish films; and this careful preparation is chiefly for the purpose of ensuring the formation of surface films with a minimum of impregnation. In fact, the preservation of the continuity of these films appears to be vital to the dielectric properties of the finished cloth, and penetration is detrimental on account of the difficulty of thoroughly oxidising anything more than a surface film, the interior parts being protected from oxidising by the hardening of the outer skin.

The varnish is applied by passing the prepared cloth through a tank of varnish which is " thinned " to a suitable extent with benzene or other solvent.

The tank is usually situated on the ground floor of a tower-shaped building, and the cloth passes upwards through drying chambers which extend to the top of the building, the speed, temperature, and other conditions being so regulated that the varnish is dry or sufficiently so for the cloth to be handleable by the time it again reaches the bottom of the building. It is then hung in long vertical loops in order

* The superoxidation referred to under Design, page 209, refers to further oxidation of linoxyn under the extraordinarily severe condition of exposure to nascent ozone.

to facilitate the complete oxidation of the varnish. Arrangements are made for successive immersions in the varnish tank if necessary.

In some cases the cloth is cut on the " bias," *i.e.* so that the warp and weft run diagonally across the piece instead of longitudinally and laterally. This entails joints at frequent intervals (*i.e.* $\sqrt{2}$ times the width), the cloth being cut across at an angle of 45° and the original edges stitched together to make a continuous length. Tapes cut from " bias " cloth are more flexible than tapes cut from the straight cloth, and by distorting under tension are more easily laid flat on irregular or curved

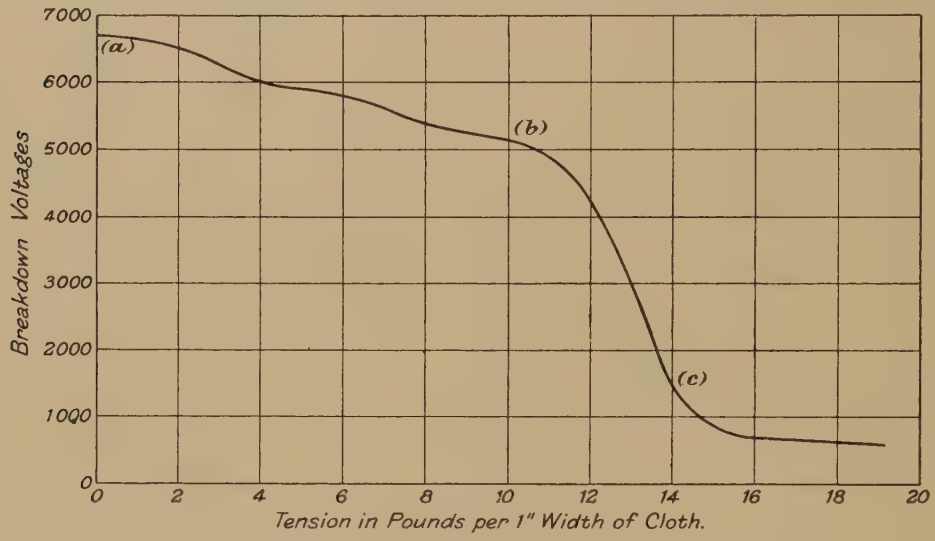

Fig. 11.—Breakdown Voltage of Varnished Cambric under Tension.

conductors such as field or armature coils. This is of little or no advantage for cable work, especially in view of the disadvantage of frequent joints.

Further, as the insulating properties (especially the dielectric strength) depend largely on the continuity of the surface films of varnish, it is obviously undesirable to unduly stretch or distort the fabric on which they are built up.

The curve, Fig. 11, reproduced by kind permission of the Ioco Rubber and Waterproofing Co., Ltd., of Glasgow, illustrates the effect of the breakage of the varnish films on the breakdown voltage of the bias-cut material. It will be seen that the dielectric strength remains reasonably constant near the original value, (*a*), until a critical point, (*b*)—evidently the elastic limit of the varnish films—is reached, after which it falls away to a value (*c*), which is hardly more than that which the unvarnished fabric would show.

The final product is put on the market in the form of rolls of cloth or discs of cut tape in standard widths, the ends or cut edges being coated with paraffin wax to exclude moisture.

The fabric as a whole, however, is seldom, if ever, free from moisture, as may be shown by immersing a sample in molten wax at 270° to 280° F., when the moisture will

be expelled (in the form of small bubbles of water vapour) freely from cut or torn edges, and somewhat reluctantly from the surfaces.

As mentioned in Chap. I, varnished cambric is not one of the materials which the cable-maker (at least in this country) produces for himself; and as, until latterly, practically all British supplies came from Continental and American sources, his requirements as to freedom from moisture were not commercially attainable.

It should be observed that the presence of moisture is comparatively unimportant when the varnished cambric is used under conditions which permit "breathing," *e.g.*, in machine insulation, where the moisture may be gradually expelled as the machine warms up; but as in cable dielectrics such "breathing" facilities are absent, steps should always be taken to eliminate the last traces of moisture before application of the varnished cambric to the conductor.

CHAPTER V

PROTECTIVE AND PRESERVATIVE MATERIALS

As indicated in the tree index shown in Chap. II, materials under this category embrace sheathing, armouring, bedding, serving, taping, braiding, and compounding materials.

Apart from efficiency of application, the purity and technical quality of them have a very marked influence on the durability of cables, because in many, if not most, conditions of use, external conditions are far more onerous than internal ones. It may also be noted that the importance of this point is liable to be overlooked by purchasers to whom price is a first consideration, and who do not appreciate the large proportion which these components bear to the total cost, although the specifications of the leading consultants and corporation engineers show a growing tendency to take care of the matter.

The term " sheath " as applied to electric cables of the kind to which this work refers, implies a continuous homogeneous covering of impervious material, applied over an insulated conductor or an assembly of insulated cores, for the purpose of protecting it or them from moisture, chemical attack, or mechanical damage.

Sheaths may be composed of metallic or non-metallic materials, the former being almost invariably lead or an alloy thereof, and the latter vulcanised rubber, vulcanised bitumen, or some special material of generally similar character.

The non-metallic sheathing materials do not differ fundamentally from materials of the same type, which are used for insulating purposes ; and as these have already been dealt with, it remains to consider—from the view-point of the present chapter—the metallic sheathing materials, viz., lead and appropriate alloys of lead, the said alloying being practically confined to small proportions of tin and antimony.

Before proceeding to consider the properties and characteristics which render lead and its alloys particularly suitable for the purposes of the cable-maker, a few notes on its origin and production may be desirable.

The ores of lead are abundantly distributed throughout the world in the rocks of all geological formations from the granite to the triassic formation, the principal one being the sulphide, galena (PbS). Those next in importance are cerussite and anglesite, both of which represent oxidation products of galena in different degrees, the former being the carbonate ($PbCO_3$) and the latter the sulphate ($PbSO_4$) ; they are usually found in association, and naturally nearer the surface than the unoxidised sulphide ore.

Considerable galena deposits exist in this country in forms which are distinguished by the miners as " rakes," which are true veins, " pipes," which are narrow oblong masses lying parallel to the rocky strata, and " flats," which are small beds of ore, more or less isolated between the strata. They are worked—in some cases in more or less desultory fashion—in the Leadhills District of Scotland, the Alston Moor area on the borders of Cumberland, Northumberland, and Durham, the Ashover District of Derbyshire, in North Wales, and to some extent in Cornwall and

Devon.* In some instances the working is only incidental to the mining of fluor spar, quartz, and other comparatively valuable minerals in association with which it occurs.

By far the largest deposits of galena occur in Canada, Australia, U.S.A., and Spain. They are usually associated to varying extents with the sulphides of other metals, such as zinc, copper, iron, and silver, and to a lesser extent, antimony and bismuth ; and therefore, while the refining processes are designed to recover the silver and remove the other metals to the greatest practicable extent, traces of some of them always exist in the commercially pure metal.

The preparation of the ore for smelting and refining is carried out by the ordinary well-known metallurgical processes, the procedure being varied according to the composition.

The actual smelting operation and the design of the furnace employed also depends largely on the character of the ore.

Three general lines of operation are practised, the principal being the " Roast-Reaction " process, in which the galena is first " roasted " in presence of air in order to partially convert it into PbO and $PbSO_4$. The air supply is then excluded and the temperature raised to produce a reaction between these compounds and the remaining sulphide, thus :—

$$PbS + 2\,PbO = 3\,Pb + SO_2,$$
$$\text{and } PbS + PbSO_4 = 2\,Pb + 2\,SO_2.$$

This method is applicable to the best types of ore, and is carried out in a reverberatory type of furnace, the charge being raked on to a sloping hearth at the back of the furnace for the second part of the process, and " rabbled " with rabbling irons from time to time in order to free the globules of molten lead from the pasty mass, and allow it to run down into a well, from which it is tapped off at intervals into moulds.

The second method, known as the " Roast-Reduction " method, is designed to deal with the poorer kinds of ore, imperfectly separated from pyrites, blende (the sulphides of iron and zinc respectively), and siliceous matter. The ore is roasted to a fairly complete state of oxidation, and then reduced by heating in admixture with coke. The roasting may be carried out on hearths, and the reduction in blast furnaces.

The third method, now almost obsolete, is called the " Precipitation " method, in which metallic iron is employed in a blast furnace to effect the decomposition of the ore at a high temperature according to the equation $PbS + Fe = Pb + FeS$. While this process avoids the preliminary roasting operation, it is only applicable to galena of a high degree of purity, as the iron reduces other metals as well as lead, thus tending to include them in the final product. It is also slow and costly.

It will be apparent that the actual operations outlined above are, in practice,

* It is of interest to note that many of the deposits in this country were worked by the Romans, and before them in some cases by the Britons. The author has frequently seen evidence of this in the Ashover mines.

much more complicated than can be here described. For example, it will be clear that a balance of the quantities of the components involved in a given reaction cannot be accurately attained, nor can it be held during manipulation of the charge on the furnace bed, and therefore subsidiary operations are entailed.

Further, for reasons connected with the residual products of the processes, a combination of the features of two of them may be necessary in order to deal effectively with a given class of ore, and therefore one type is not exclusively used in any refinery.

The lead, as obtained from the smelting furnaces, is subsequently, in order to render it marketable for ordinary technical purposes, subjected to refining processes. These vary in detail according to the character of the impurities contained in it. When silver is present in such proportion as to make its recovery remunerative (normally in the neighbourhood of 4 oz. to the ton), the processes naturally centre round this operation. Broadly speaking, liquation, oxidation, and drossing processes are employed to remove the majority of the contaminating metals, but silver is not susceptible to this type of treatment. This is exemplified by the fact that in a pig of smelted lead, all the impurities are concentrated towards the top surface, with the exception of silver.

The affinity of lead for silver thus indicated is well known by metallurgists to be such that it will even remove the silver from other alloys. Zinc, however, alloys even more readily than lead with silver, and a desilverising process, invented by Mr Alexander Parkes, of Birmingham, in 1850, is based on this fact. A small quantity of zinc is introduced into the molten argentiferous lead at a temperature exceeding the melting-point of zinc, and the whole thoroughly stirred. On being allowed to cool, the part which solidifies first and forms a crust on the surface consists of the silver-zinc alloy, with a certain amount of lead, which is skimmed off. The operation is repeated, sometimes more than once.

In order to remove surplus zinc, the lead is subjected to one or other of the oxidising treatments above referred to, which are known as " improving " or " softening " processes. Incidentally, such processes are sometimes used prior to desilverising, particularly when antimony, copper, and other oxidisable metals are present in sufficient proportion to interfere with desilverising operations.

Another widely used desilverising process is the Pattinson process, which is dependent on the fact that when molten argentiferous lead is allowed to cool slowly, with constant stirring, crystals of comparatively pure lead begin to separate out, and these can be ladled out, leaving behind an alloy correspondingly rich in silver. This operation is repeated in a series of pots, so that eventually the main body of lead is obtained practically free from silver, and a residue of lead, which is rich in silver, is separated for further recovery treatment by cupellation.

Incidentally, certain other metallic impurities such as antimony, copper, bismuth, nickel, and arsenic are removed by this process.

As is well known, the hardening effect of even small quantities of such metals as antimony, copper, arsenic, and tin is remarkable, and apart from any effect which impurities may have on the durability of cable sheaths, it is of great importance to

TABLE VI—Analyses of Various Brands of Commercial Lead

	Raibl, Carinthia	Przibram, Bohemia.	Hoboken, Antwerp.	Monteponi, Sardinia.	Enthoven, London.	English Chemical.	B.H.P. Port Pirie, Australia.	B.H.P. Port Pirie, Australia.	Lone Elm, Missouri.	St Joseph, Missouri.	Argentine, Kansas.	Selby, California.	Trail, B.C.
Reference,	1	2	3	4	5	6	7	8	9	10	11	12	13
Process,	A	C	D	D	A	?	D	D	B	D	D	D	E
Pb	99·98299	98·9841	99·9903	99·9980	99·9851	99·9693	99·9913	99·9853	99·97204	99·91680	99·99249	99·9579	99·9890
Cu	·00069	·0024	·0015	·0005	none	·0097	·0004	..	·01782	·06400	·00022	..	·0003
Sb	tr.	·0056	·0030	·0030	·0160	·0149	·0051	·0108	·00146	·00130	·00127	..	..
As	tr.	..	·0005	..	..	·0002	tr.	..	·00011	·00080	tr.	·0024	·0020
Bi	..	·0023	..	·0007	·0048	tr.	..	..	..	..	·00308	·0300	..
Ag	·00025	·0018	·0004	·0010	·0015	·0020	·0008	·0009	·00056	·00007	·00020	·0010	·0025
Fe	·00055	·0017	·0008	·0047	·0026	·0029	·0015	·0025	·00686	·00100	·00178	·0027	·0053
Mn	..	..	..	..	..	..	..	..	..	..	·00021	·0008	..
Ni	..	·0011	·0005	..	tr.	·0003	..	..	·00077	·01600	tr.	·0001	tr.
Co	..	..		..	tr.	tr.	tr.	tr.	·00005		..	..	..
Zn	·00076	·0010	·0030	·0021	tr.	tr.	·0009	·0001	·00033	..	·00075	·0003	·0002
Cd	..	..	..	..	tr.	·0007	tr.	tr.	..	..	..	tr.	..
Sn	..	..	..	..	..	..	..	·0004	..	..	..	·0004	·0007
S	·01476	..	..	..	..	..	tr.	..	..	..	..	..	..
Insol.	..	..	..	..	tr.	tr.	..	tr.	..	..	..	·0040	tr.
	100·00000	100·0000	100·0000	100·0000	100·0000	100·0000	100·0000	100·0000	100·00000	99·99997	100·00000	99·9996	100·0000

Note.—In all the above analyses, except Nos. 10 and 12, lead has been determined by difference.

Process.—A = Reverberatory; B = Hearth; C = Blast-furnace followed by Pattinson; D = Blast-furnace followed by Parkes' process; E = Electrolytic.

References.—1. *Oesterr. Jahrbuch des K. K. Berg-Akademien*, vol. xxii., p. 389. 2. *Oesterr. Zeitschrift f. B.- u. H.-wesen*, 1885, p. 208. 3. Firket, *Annales des Mines de Belgique*, 1901, p. 237. 4. Ferraris, *Oesterr. Zeitschr. f. B.- u. H.-wesen*, p. 455, and *E. and M. J.*, 28th Oct. 1905, p. 784. 5, 6, 8, 12, and 13. *Engineering and Mining Journal*, vol. lxxxiii., 22nd June 1907, p. 1179. 7. *Private Notes*, 1896. 9. *Trans. A.I.M.E.*, vol. xviii., p. 687. 10. *Min. Ind.*, xiii., 1905, p. 274. 11. *Engineering and Mining Journal*, 14th July 1882.

the cable-maker, from the manufacturing point of view, that the lead he uses should be uniformly soft. There is no difficulty in ensuring this, as the best brands of lead can be relied on to be within 0·02 per cent. of absolute purity, as shown by the preceding Table, taken from *The Metallurgy of Lead*, by H. F. Collins, by kind permission of Messrs Charles Griffin & Co., Ltd., owners of the copyright.

With regard to the physical properties of lead, its chief characteristics by comparison with other common metals lie in its high specific gravity, which varies from 11·254 in cast to 11·395 for rolled metal, its low melting-point (327·4° C.),* and

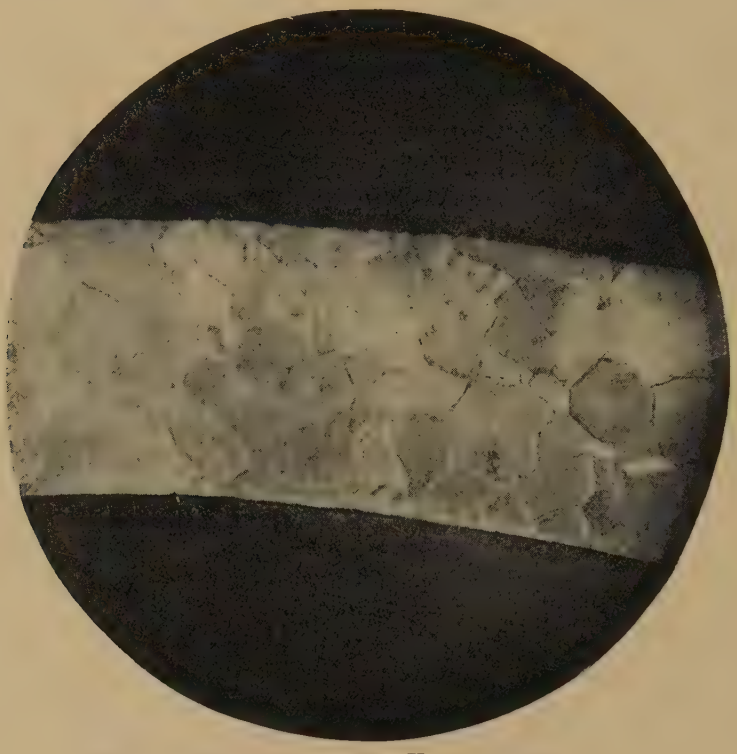

Fig. 12.—Photomicrograph of Hot-extruded Lead.
(Magnification × 12.)

its extreme softness, which allows it to be readily cut with a knife, and to mark paper with a grey metallic streak when drawn across it.

It is very malleable, even in the cold. Professor Spring,† of Liège, determined experimentally, many years ago, that in the form of filings it became a solid mass under a pressure of 13 tons per sq. in., and liquefied at 33 tons per sq. in.

Its malleability, combined with its softness, renders it readily amenable to rolling and extrusion operations in manufacture. Its tenacity is, however, very low (of the order of 1800 to 2200 lbs. per sq. in.), and its elastic limit negligibly small,

* *Metallurgy of Lead*, H. O. Hofman, 1st Edition, p. 9.

† *Ann. Chim. Phys.*, 1881, xxii. 170 ; *Bull. Soc. Chim.*, 1883, xl. 520, 1918.

so that in spite of its great ductility, it cannot be drawn into wire. When required in this form, it is usually extruded under hydraulic pressure. There is no difficulty, however, in drawing extruded tubes down to smaller diameters; as mentioned elsewhere, this method was employed for lead sheathing cables in the early days of the industry, the cable being first drawn into a lead pipe.

Its coefficient of linear expansion, $0{\cdot}2924 \times 10^{-4}$ (at 40° C.), is greater than that of any other metal except zinc.

Other properties of lead which are of importance to the cable-maker are its

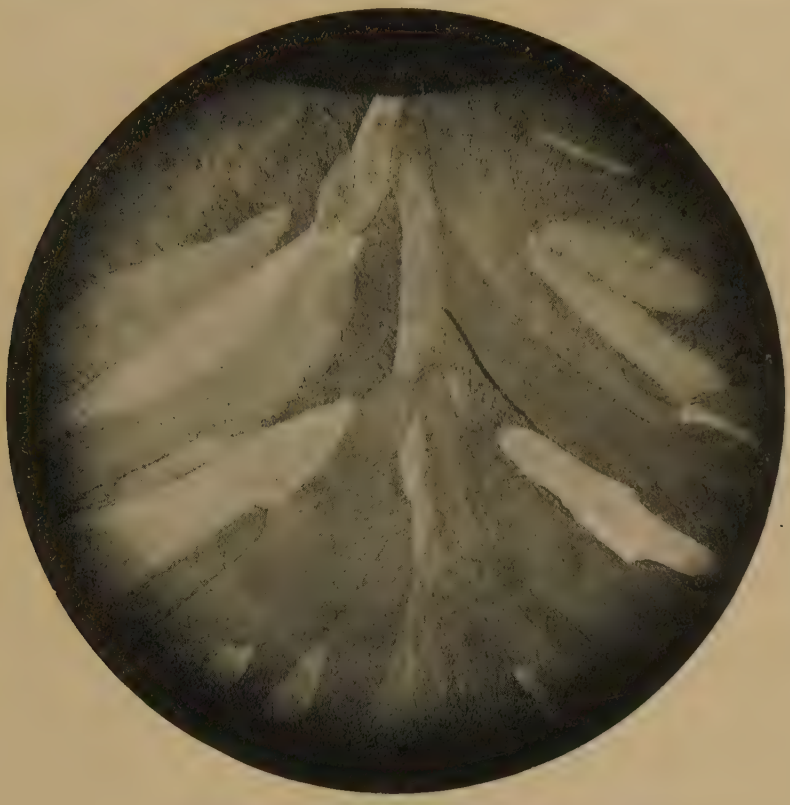

FIG. 13.—PHOTOMICROGRAPH OF TRANSVERSE SECTION OF CAST-LEAD SLAB.
(Magnification × 12.)

thermal and electrical conductivities, both of which are comparatively poor. With regard to the former, Wiedemann and Franz found it to be 8·5, as compared with silver=100. It must be remembered, however, that this value is high by comparison with the heat conductivity of other components of a cable exterior to the conductor. The surface emissivity of lead is of appreciable importance; values have been determined by Mr J. F. Watson,* for new and dull black-painted sheaths of 0·00070 watts per degree C. per cm². for the former, and 0·00107 for the latter.

Freshly cut surfaces of lead show a bright metallic lustre, which, however, soon

* "Second Report on the Heating of Buried Cables," *I.E.E., Journal*, vol. 61, p. 551.

disappears owing to superficial oxidation. It has a pronounced crystalline structure, the octahedral form of which can be easily demonstrated by allowing the molten metal to partially solidify, and then quickly pouring off the remaining liquid portion, or by shaking or tapping the vessel containing it at a critical moment when the temperature is approaching the setting-point.

Fig. 12 illustrates the normal crystalline structure of lead in cable sheaths formed by hot extrusion under heavy hydraulic pressure.

Cold worked lead acquires a very fine structure, while, on the other hand, cast

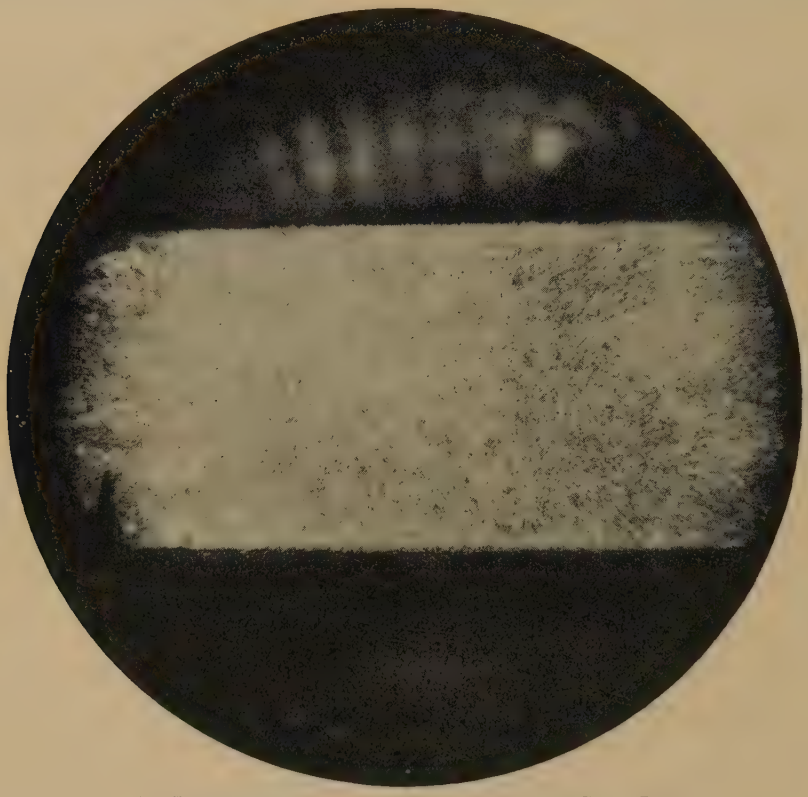

Fig. 14.—Photomicrograph of Cast Lead after Cold Rolling.
(Magnification × 12.)

lead shows large crystals, which set themselves in angular fashion from the centre to the outer boundaries of the casting in a manner dependent on the rate of cooling.

Although, so far as present knowledge goes, no appreciable technical disadvantage arises from a moderate degree of variation in crystalline structure, it is of interest to note the relation between various structures, as shown in the accompanying photomicrographs taken in the course of a recent research on the annealing of lead carried out by the author.

Fig. 13 shows a typical cast lead structure, and represents a transverse section through a small cast slab (3 in. × $\frac{1}{2}$ in. × $\frac{1}{2}$ in.).

Fig. 14 shows the fine structure produced by cold rolling the slab; while Fig. 15 shows the effect of annealing it for nine days at 350° F.

It will be seen by comparison of Fig. 15 with Fig. 12 that the normal structure of an extruded cable sheath is fairly comparable with that resulting from approximately complete annealing.

As regards electrical conductivity, it is found in practice that the average value for lead in the form of extruded cable sheaths is very closely and uniformly equal to one-twelfth of that of annealed copper, and has a temperature coefficient of

Fig. 15.—Photomicrograph of Annealed Lead.
(Magnification × 12).

0·387 per cent. per ° C. at 20° C. (The importance of the electrical conductivity of metallic sheathing materials is referred to under Design, Chap. XI, p. 254.)

With regard to chemical properties, pure commercial lead is readily dissolved by nitric acid, but resists the action of dilute hydrochloric and sulphuric acids in the cold, and is but slowly attacked by them even when boiling. Organic acids, such as acetic, tartaric, and citric, attack lead in presence of air and moisture; in fact, corrosion of sheet-lead by acetic acid under these conditions, in conjunction with a supply of carbon dioxide, forms the basis of the well-known Dutch process of manu-

facturing the basic carbonate of lead known as white lead. Electrolytic corrosion occurs very readily under practically any condition which permits the passage of a current of electricity to or from it by an electrolytic path ; and, as mentioned elsewhere, Vol. II (Causes of Deterioration), the lead compound resulting from the action depends on the character of the electrolyte, the current density, the degree of exposure, and generally on local conditions, *e.g.*, the oxides, the carbonate, or the plumbate. Unlike most of the purely chemical actions on lead, electrolytic action penetrates continuously the whole thickness of metal exposed to it. For example, the entire radial thickness of a cable sheath may be converted into litharge under suitable conditions of exposure.

Under normal conditions, however, the resistance of lead to corrosion is considerable. The combined action of air and water, either water containing dissolved air, or air in presence of moisture, will produce the hydroxide, which dissolves in the water and becomes converted into carbonate by the carbon dioxide in the air.

This action is quite superficial, and does not penetrate to an appreciable depth, because the carbonate, like the chloride, sulphate, and fluoride, forms a protective film against further action.

It is therefore important to determine whether signs of corrosion which may exist on a lead sheath are due to simple chemical action or to electrolytic attack.

The effect of water on lead varies somewhat according to the presence of small quantities of salts in solution ; for example, nitrates assist the action, while chlorides, sulphates, phosphates, and carbonates are stated to reduce it.

Although for ordinary power and lighting cable sheaths only the purest commercial soft lead is used, it is common practice to alloy it with either 3 per cent. of tin or 1 per cent. of antimony, for the purpose of sheathing air space (" dry core ") telephone cables, in order to prevent distortion or partial collapse from the original circular section to an elliptical form during winding or installing. Alloying of this character stiffens the sheath considerably, and is said to increase its tenacity to about two and a half times that of the lead.

These alloys or some modification of them are also employed in sheathing rubber insulated wires used in certain surface wiring systems,* the object being to stiffen the wire as a whole, so that it needs less frequent support in running it along walls or ceilings, and incidentally to render it more resistant to mechanical damage.

As mentioned elsewhere (Manufacture. Vol. II), these alloys are considerably more difficult to extrude than pure lead.

Another type of hard metal sheath consists of a longitudinal strip of sheet brass or tinned copper, folded around the circumference and soldered or brazed to make an impervious covering.

* Clause 76 (*g*) of the eighth edition of the *Regulations for the Electrical Equipment of Buildings* (formerly *I.E.E. Wiring Rules*) relates to the use of cables " sheathed with a closely fitting seamless covering containing not less than 95 per cent. of commercially pure lead (the remainder consisting of rarer metals), and in other respects complying with . . ."—another clause governing radial thickness, which has to be in accordance with British Standard Specification, No. 7.

METALLIC (ARMOURING)

Armouring.—The mechanical protection of cables used for power and lighting mains, etc., invariably consists of steel tape or galvanised steel wire.

The former is generally applied to cables laid direct in the ground, and the latter used in connection with cables for colliery work, or in other situations where tensile strength requirements are entailed.

Steel Tape.—The steel for this class of work is usually made by the Siemens Martin basic process, which results in a uniform product, containing only a very small percentage of the two most objectionable impurities, viz., sulphur and phosphorus, which are inevitably present in varying quantities in all steels.

The production of steel tape broadly follows general rolling mill practice, which is outlined under Manufacture, Vol. II.

It is desirable that the steel tape used for armouring should be of medium hardness, so that whilst affording the necessary mechanical protection, such as withstanding a blow from a pick during excavation work, it should not unduly interfere with the flexibility of the cable, nor—in the case of small cables—cause risk of damage or distortion of the underlying cable during application.

An indication of the suitability of steel tape may be obtained by the tensile strength and elongation, and this test is sometimes specified. For instance, Government Department Electrical Specification, No. 1, states: "The tensile strength of the tape shall be not less than 20 nor more than 28 tons per square inch. The elongation of the test piece (8 inches long) shall be not less than 15 per cent." These limits may be taken to represent a suitable quality for general purposes.

Steel tape is used in varying widths and thicknesses, according to the size and type of cable to which it is applied. The width varies from $\frac{1}{2}$ inch to 2 inches, and the standard thicknesses are ·030 in., ·040 in., and ·060 in., a tolerance of 3 mils usually being allowed on the thickness.

The tape should be free from rust and scale, and possess a perfectly clean surface.

Certain specifications call for galvanised steel tape, and an additional test for this material is the galvanising test, fully described in connection with the testing of galvanised steel wire.

Galvanised Steel Wire.—The most suitable quality for this purpose is mild steel wire having a breaking strain of 25 to 30 tons per square inch. In certain cases elongation limits are also defined.

The production of steel wire closely follows that of copper wire, described under Manufacture, Vol. II.

Various tests are specified, both as regards quality of wire and adhesion and thickness of the galvanising. In addition to the tensile test, a torsion test is usually required. With regard to the galvanising, a chemical test, designed to determine the thickness and uniformity of the zinc coating, consists of periodic immersions in

a saturated solution of copper sulphate. A mechanical test is also carried out to determine the adhesion of the galvanising, which consists of wrapping the wire round a rod of five to ten times the diameter (according to the size) of the wire. These tests are fully described under Testing.

In addition to the usual form of "single" and "double" wire armour, to which the above remarks apply, certain types of flexibles are armoured with an open spiral of galvanised steel wire, for which a special smooth finished quality is used.

Metallic protection in the form of wire braids is sometimes employed, chiefly on small and medium sizes of cables, especially those of a flexible nature. Various types of wire are used according to the class of cable and the particular protection desired. Tinned copper wire braid is used on small flexibles for certain types of automobile lighting and ignition flexibles.

Tinned steel or galvanised steel wire braids are used for protective purposes on the more robust type of flexibles, and phosphor bronze is also used to some extent for special purposes.

"Half-round" or D-section strip is used extensively for armouring automobile starter and lighting cables, and is applied in the form of a close spiral. Brass, aluminium, and nickel or nickel alloys are the materials most commonly used.

FIBROUS (BRAIDING)

The fibrous coverings employed in the construction of cables for their chemical preservation and mechanical protection (these two functions being largely interdependent) are of three general types, viz., braidings, tapings, and lappings. Whether woven before application to the cable, as in the case of tapes, or woven on the cable, as accomplished by braiding, or by winding on warps without weft, as in lappings, they virtually constitute fabric encasements.

For their own preservation, and also in order to attain the desired chemical protection for the underlying cable, they are treated in various ways with appropriate materials so as to coat and/or impregnate them suitably for their purpose; and subsequently, after forming upon or applying to the cable, they are further treated to complete the filling and sealing of all spaces which might form communications between the underlying cable and the exterior surface and surroundings.

Braiding is the most effective (and incidentally the most expensive) method of applying fibrous coverings, from the point of view of uniformity of construction and suitability for treatment with preservative compounds. Being woven as a continuous envelope on the surface of the cable, braidings are naturally more resistant to wear and less liable to disturbance than tapings or lappings, and are consequently always used where such influences come into play.

The yarns used for braiding vary according to the purpose for which the cable is to be used and the manner of such use. Naturally the radial thickness of the

braid increases as the size and weight of the cable increases. Cotton and jute are the materials most commonly used, and as the length and fineness of the original fibre determine the ultimate fineness to which a yarn may be spun, cotton is more suited to small wires and cables, and jute to the larger sizes.

Hemp and flax are intermediate in this respect, and are sometimes used in place of cotton when a more robust covering is necessary.

Other yarns, etc., referred to in this section, are used for various definite purposes, such as genappe (a form of worsted) and asbestos to attain fire-resisting properties, silk for ornamental purposes, and cords or leather strip for special mechanical protection.

Cotton.—A limited reference to this material has already been made in connection with the manufacture of paper, the sources of origin and microscopic features of the fibre being briefly mentioned. A detailed description of the processes involved in converting the raw fibre into yarn suitable for the cable manufacturer is beyond the scope of this work, but a brief reference at this point may be interesting.

Raw cotton is shipped to this country in compressed bales, which usually contain appreciable quantities of impurities, such as mineral earthy matter, and vegetable matter associated with the plant. The first process on arrival at the mill is the opening-up of the bales and elimination of as much of this foreign matter as possible.

This is followed by the " carding " process, which consists of eliminating the short fibres and more persistent impurities, and also arranging the individual fibres in a more or less parallel position. The cotton issues from the carding machine in the form of an untwisted rope, known as a " sliver."

At this stage the cotton is subjected to a drawing process, which consists of passing a number of the slivers through revolving rollers.

The dominating idea throughout these processes is to produce a rope, or strand, of uniform weight per length, with the fibres in a longitudinally parallel direction, in readiness for the subsequent spinning operations.

The next operation (a further drawing process) is known as " slubbing," in which an appreciable reduction in diameter from the drawn sliver occurs. A certain amount of twist is introduced during this process, in order to strengthen the strands of cotton fibre; finally it is wound on bobbins, from which it is spun into yarn on the spinning machine.

The counts of cotton are calculated in the following manner. The basis may be described as " hanks per lb." (the hank measuring 840 yards).

For example :—

" 10's " cotton = 840 yards × 10 = 8400 yards per lb.
" 20's " ,, = 840 yards × 20 = 16,800 ,, ,,
" 20's/2 fold " = 840 yards × 20 ÷ 2 = 8400 ,, ,,

From the following Table the counts of yarn may be readily determined. By measuring 840 yards of any size of cotton yarn (from 5's to 60's), determining the

weight in grammes, and referring to the Table, the nearest " count " or number will be observed.

TABLE VII

Table for Numbering Yarns

No.	Grammes.	No.	Grammes.	No.	Grammes.	No.	Grammes.
5	90·72	19	23·87	33	13·75	47	9·65
6	75·60	20	22·68	34	13·34	48	9·45
7	64·80	21	21·60	35	12·96	49	9·26
8	56·70	22	20·62	36	12·60	50	9·07
9	50·40	23	19·72	37	12·26	51	8·90
10	45·36	24	18·90	38	11·94	52	8·72
11	41·24	25	18·14	39	11·63	53	8·56
12	37·80	26	17·45	40	11·34	54	8·40
13	34·89	27	16·80	41	11·06	55	8·25
14	32·40	28	16·20	42	10·80	56	8·10
15	30·24	29	15·64	43	10·55	57	7·96
16	28·35	30	15·12	44	10·31	58	7·82
17	26·68	31	14·63	45	10·08	59	7·69
18	25·20	32	14·17	46	9·86	60	7·56

" 36's " cotton yarn (50,240 yards to the lb.) is the size most commonly used for wires and cables of small diameter, through a range of intermediate sizes or " counts " to a maximum of 10's/2 fold (5's equivalent, 4200 yards to the lb.) for the larger sizes.

Coloured cotton is sometimes used for distinguishing purposes; self-colours, combinations of colours, or simply a tracer thread of distinctive colour may be used.

In cases where the braid is subjected to treatment by preservative materials such as ozokerite and similar compounds, " soft " cotton yarn is employed, but where no such subsequent process is carried out, " polished " or " glacé " cotton is used

Glacé cotton is used chiefly for flexibles, such as the twin flexible, used for pendant lights; other examples are dynamo flexibles, and flexible leads used for a variety of purposes for inside situations, where they are not subjected to rough handling or abrasion.

The smooth finish of glacé cotton is obtained by treatment of the ordinary cotton yarn with a sizing or dressing material, in order to " lay " the fibres, and polishing with revolving brushes after winding the cotton on a suitable frame. A 2-fold yarn is generally used, and the size is calculated in the same manner as for soft cotton yarn.

Jute.—Next to cotton, jute is the commonest yarn used for braiding purposes. It is obtained from the *Corchorus capsularis* and *Corchorus olitorius*, which are cultivated chiefly in India, and also to some extent in China and the Malay Peninsula.

The plants are either cut down or uprooted and subjected to "retting"; this process consists of packing the stalks in bundles, which are immersed in water for two or three weeks and allowed to rot. At this stage the useless portion is separated, and the fibrous portion is washed, dried, and finally packed in bales.

Apart from a softening process which is necessary on account of a certain harshness or brittleness of the fibre, the production of yarn more or less follows that of other yarns of this class.

Jute is used for the larger type of rubber-insulated cables, as in the case of cotton, mainly as a final covering, in which case it is passed through a bath of preservative compound such as ozokerite.

Jute is eminently suitable for braiding the larger sizes of rubber cable, and for all sizes of bitumen and similar types of cable, because it is of a coarser nature, and therefore gives a sufficiently heavy radial thickness of covering without entailing undue density, and thus militating against proper penetration of the preservative compound with which the braid is finally treated.

The yarn may be plain, *i.e.* untreated, or it may be tanned or "cutched," when it is required to be specially protected from rotting influences such as exist in damp situations, and which can only be in part combated by compounding the complete braided covering.

Cutch, an extract obtained from various species of acacia which grow chiefly in India, is the tanning agent commonly used for treating jute yarn.

Another type of preparatory treatment which the author has found to be effective against infection of the braid by dry rot or similar fungoid growth is to impregnate it with creosote oil or a creosote-pitch mixture, the excess being removed from the bobbins or hanks by centrifugal action.

The basis for calculating the size of the finer jute yarns is the "lea," which is equivalent to 300 yards. For example :—

10 lea jute yarn =300 yds. $\times 10$ =3000 yds. per lb.
7 „ „ =300 „ $\times$ 7 =2100 „ „

By measuring 300 yards, determining the weight in grammes, and referring to the numbering table, the size of jute may be ascertained in the same manner as cotton.

The larger sizes of jute (see "Lapping," p. 122) are numbered according to the "weight per 100 gross yards," thus "30 lb." jute yarn indicates that the weight of 14,400 yards equals 30 lb., similarly "48 lb.," "72 lb.," yarn represents the weight per 14,400 yards in each case.

Flax is obtained from the bast fibre of the plant *Linum usitatissimum*, which is cultivated in various parts of the world, notably Russia, Belgium, Northern Ireland, and Holland. It is grown either for the seed (from which linseed oil is expressed) or for the fibre, but seldom for both. When cultivated for the fibre, the plant is usually uprooted before the seeds ripen.

The plant is next subjected to "retting" by immersion in stagnant pools, in order to separate the woody matter from the fibre. On the completion of this operation the bundles are allowed to drain, and subsequently dried in the open.

This process is followed by " scutching " or cleaning, in order to eliminate the useless fibrous matter.

At this stage it is ready for the spinning mill, and after a preparatory treatment known as " hackling," which is more or less a combing or carding operation resulting in separating and drawing the fibres in a longitudinal direction, the material is ready for the preliminary operations in the spinning process, which are more or less common to this class of fibre.

The measurement of flax yarn is based on the " lea " (300 yards), as in the case of jute. For example :—

20 lea yarn $=300$ yds. $\times 10 = 3000$ yards per lb.
35's/2 fold ,, $=300 \times 35 \div 2 = 5250$,, ,,

By obtaining the weight of 300 yards and referring to the Table, the size of any yarn may thus be obtained.

Hemp (common), which is a somewhat coarser fibre than flax, is obtained chiefly from the *Cannabis sativa*, grown largely in Russia, Italy, and to some extent in India.

It is a bast fibre, and is separated from the woody matter in much the same manner as flax. The fibre cultivated in Italy is superior to the Russian product, and for this reason Italian hemp is often specified for braiding purposes.

The size of hemp yarn is based upon the weight per nautical mile (2029 yards). For example, " 4 oz." hemp yarn weighs 4 oz. per 2029 yards.

The quality and uniformity of hemp yarn is to some extent ensured by specifying a minimum breaking strain, and it is generally expressed in the following terms : " The breaking load of the hemp shall be not less than seven pounds per pound weight per nautical mile," which interpreted means that a " 16-oz." yarn shall have a breaking strain of not less than 7 lb., and similarly an " 8 oz." yarn shall have a minimum breaking strain of 3·5 lb.

Both flax and hemp are superior to either cotton or jute, both in strength and resistance to deteriorating influences. The liability of jute to hydrolyse in the presence of moisture has already been noted.

Asbestos Yarn.—Asbestos in the form of yarn, used almost exclusively in cable-making on account of its well-known heat and fire-resisting properties, differs from the other fibrous materials inasmuch as it is of mineral origin. The mineral known as chrysotile (which is the white variety) occurs in veins running through rocks located chiefly in certain parts of Canada, notably Quebec.

Asbestos yarn is produced by subjecting the fibre to similar processes to other textile fibres, but reference to the photomicrograph of the asbestos fibre (Vol. II), and comparison with fibres of vegetable origin, will reveal the physical difference and emphasise the difficulties of producing asbestos yarn; these remarks apply particularly to the spinning process.

Fire-resisting compound or paint is usually applied to asbestos-covered cables during the braiding operation, and this method fills the interstices of the braid very effectively.

There is no recognised standard for the numbering of asbestos yarn, and it is

usually left to the manufacturers to supply a designation, and a check may be made by ascertaining the length per lb.

Pure asbestos only should be used in the production of the yarn to obtain the most efficient results, although admixture with cotton is sometimes made, with a corresponding reduction in the fire-resisting property. Such adulteration may be detected by microscopic examination.

Genappe is a smooth worsted yarn produced by burning off the surface fibre in order to produce a more lustrous thread. Being of animal origin—as distinct from the vegetable or mineral sources from which the previously mentioned yarns are derived—it differs in composition and structure from them, and as a consequence the treatment it receives, prior to the spinning process, is of a specialised nature.

The fire-resisting property of wool is well known, and although not quite equal to asbestos in this respect, it possesses greater mechanical strength and is capable of being spun into a more uniform yarn. In combination with fireproof paint servings it produces a fire-resisting covering which is excellent from both the technical and economic points of view.

The size of worsted yarn is calculated as 560 yards to the hank. For example :—

$$\begin{aligned} 20\text{'s yarn} &= 20 \times 560 \quad\quad = 11{,}200 \text{ yards per lb.} \\ 40\text{'s/2 fold} &= 40 \times 560 \div 2 = 11{,}200 \quad \text{,,} \quad \text{,,} \quad \text{,,} \end{aligned}$$

For the purpose of ascertaining the size from the Table, the weight in grammes of 560 yards is obtained.

Silk.—Both natural and artificial silk are used for braiding, chiefly on the twin flexible type of cable, the former, however, being used only to a limited extent on account of the cost. Silk yarn serves a decorative purpose in addition to being a light form of protection.

The basic substance in all artificial silks is cellulose, the chief differences in the production being the chemicals used to convert the cellulose into a soluble form and the subsequent dissolving process.

Recently the Silk Association of Great Britain and Ireland has adopted the word " Rayon " as a descriptive term for all types of " Artificial Silk." The object is to eliminate the use of the word " silk " in connection with the synthetic product, in order to prevent misdescription and confusion with pure or natural silk.

Ramie.—Experiments have been carried out with a view to using ramie for braiding purposes, but as it showed no advantage, either technically or commercially, over cotton yarn, its use has not developed in this direction.

Whipcord is sometimes used for the protection of cables subjected to rough handling and severe abrasion, such as trailing cables. It is manufactured from either flax or hemp fibre and forms a very efficient covering. It is desirable to treat the whipcord with preservative compound before application to the cable, owing to the fact that complete impregnation of the individual cords cannot be effected by merely passing the cable through a bath of preservative compound.

Braided cord is sometimes used, and this is also usually made from either flax or hemp yarns.

Leather strip applied in braid form * is used to some extent for the final protection of cables of the above class, although there has been a tendency latterly to replace both types by tough rubber-sheathed cables.

Owing to the open character of cord and leather braids it is advisable to apply them over an ordinary soft cotton ozokerite served braid, or alternatively, to fill their interstices with small soft yarns such as jute, applied simultaneously (in parallel) with the main members of the braid.†

A method of distinguishing cores of the same colour in a twin cable is by means of a " raised tracer thread " embodied in the braiding of one of them. This effect is produced either by increasing the number of ends of yarn on one spindle of the braiding machine, or replacing the " ends " of yarn by a single or double " end " of fine whipcord.

FIBROUS (LAPPING)

Lappings of cotton yarn for protective purposes are usually applied only to small pure rubber insulated flexibles. It may be mentioned in passing that cotton is used to a limited extent as a separator between the conductor and vulcanised rubber insulation on flexibles in lieu of pure rubber, but at the best it is a poor substitute, especially if the copper wires are untinned. Very fine counts are used for both purposes, viz., 60's, 90's, and 120's.

Uniformity and tensile strength are the most desirable properties.

Coloured cotton yarn is used to some extent for multicore flexibles for identification purposes, a large variety being obtained by the use of combinations of colours.

Silk is used in preference to cotton on certain types of small flexibles for such purposes as instrument work, where insulation resistance and small bulk are of importance. It has recently been demonstrated that artificial silk of the cellulose acetate type (" Celanese ") gives appreciable advantages in these directions.

Cutched jute in the form of lapping is used on large sizes in certain types of cable, chiefly as a bedding for galvanised steel wire or steel tape.

Asbestos yarn is sometimes applied in the form of lapping on fire-resisting cables, usually as additional protection, underneath an asbestos braid.

Tarred jute yarn is almost universally used for lapping cables for the purpose of bedding in armoured cables, and also as a final covering or " serving." " 30 lb.," " 48 lb.," and " 72 lb.," are the sizes most commonly used, and uniformity both as regards thickness and degree of impregnation are the most desirable properties. The approximate composition found to be most suitable is 65 per cent. dry jute, and 35 per cent. of tar. The size of the yarn indicates the weight of dry jute before impregnation. The lappings are, of course, served with compound during the process of application.

The radial thickness of tarred (or tanned) jute bedding, under armour, is given in British Standard Specification, No. 7

* Patent No. 8810/1903. Claremont and Beaver.

† Patent No. 5206/1912. Beaver and Claremont.

Tarred rope, applied in the form of a close spiral, is used to a limited extent on trailing cables, although as in the case of cord and leather braiding this type has been superseded latterly by tough rubber-sheath protection.

FIBROUS (TAPING)

Practically all types of tape employed in cable manufacture for protective and preservative purposes are obtained by the cable-maker in the form of cloth. In a few isolated instances woven tapes are demanded by users' specifications, but no very useful purpose is served by their employment. For reasons of convenient and economical handling in the processes of preparation to which the cable-maker has to subject it before application to the cable, it is supplied in the longest lengths and greatest widths that his proofing and impregnating machines can handle.

In some cases the cloth is specially woven; in others, a commercial grade may be utilised. Immediately after leaving the looms, the cloth is subjected to appropriate "finishing" processes, which vary according to the purpose for which the cloth is intended. For example, cloth to be used for "proofed tape," which is applied over unvulcanised rubber wires, will be "fired and scoured" in order to get rid of surface impurities and stray fibres, and then calendered; while cloth to be used for a less delicate purpose does not need such careful finishing.

Generally speaking, little else but cotton and jute are used for tapes in ordinary cable work, the former for the finer purposes, and the latter for heavier duty, such as the outer coverings of lead-sheathed or armoured cables in place of, or in conjunction with jute yarns.

The following represents the treatment applied by the cable-maker to the cloths, preparatory to cutting them into tapes and applying them to the cables :—

Material.	Treated with—	Chiefly applied to—
(1) Cotton . . .	Rubber proofing	Vulcanised rubber wires and cables
(2) ,, . . .	Bituminous compound	Bitumen insulated cores
(3) ,, . . .	Oil-resisting varnish	Flexible vulcanised rubber cables, *e.g.*, motor-car cables
(4) Cotton (or Asbestos)	Fire-resisting compound	Non-metallic sheathed cables
(5) Jute (Hessian) .	Bituminous and pitch compounds	All types. Chiefly armoured cables
(6) ,, .	Red-lead compound	Principally lead sheathed and armoured

Taking them in the above order, the primary function of proofed tape is to support the rubber during the process of vulcanisation, and generally to afford

mechanical protection during manufacture, and chemical protection thereafter. It should be a fine fabric, as thin as possible consistent with the possession of sufficient strength to withstand the mechanical stresses to which it is subjected during manufacture. It should be free from dressing and loading matter, and should be from 5 to 6 mils in thickness, and its " count " should be of the order of 75 to 85 yarns to the inch for both warp and weft. A cloth of this kind will weigh about 2 oz. per square yard, and, if the yarns are of good quality, will proof well and be strong enough for its purpose.

The proofing should fill the interstitial spaces of the weave, and provide a surface film which, while sufficient to adhere slightly to the insulation after vulcanising, will also form a cleavage line so that the tape may be readily stripped when required. If the tape is proofed on both sides (double proofed), the chemical protection afforded to the underlying rubber insulation is enhanced, as air and moisture are more effectively excluded from it. In ordinary practice, however, the preservative compound which is applied at a later stage is relied upon in this respect. The proofing is applied either by a spreading machine or a friction calender, but more usually the former, when the tape is to be applied to small wires and cables, because the coating can be formed with less increase in the thickness of the cloth than when " frictioned " on, and is less superficial in character.

The second class of tape, made from cotton cloth treated with bituminous compound, is commonly called " bitumen tape." The cloths vary in weight and texture from the fineness of those used for proofed tapes to heavy twills. Their treatment consists in thorough impregnation by passing them through suitable bituminous compounds in the molten state, excess compound being removed by heated knives or " doctors."

Bitumen tapes are of considerable general use in cable manufacture, but are chiefly employed for the protection of vulcanised bitumen cables, the fine variety being used directly over the bitumen dielectric on account of its superior flexibility, and the heavier kinds (usually described in specifications as " stout " bitumen tapes, in contradistinction to " fine ") for exterior protection.

Oil-resisting tapes are made from cloth treated in a similar manner to varnished cambric (already referred to earlier in this chapter), but the cloth is not subjected to a preliminary sizing operation, and consequently the process is one of impregnation rather than one of producing surface films of varnish. The object of using this form of varnish-treated cloth is to attain greater flexibility, and a closer adherence of the tape to the surface of the cable than ordinary varnished cambric would permit, especially in view of the fact that this class of tape is usually applied to small cables of a flexible character, such as are used for wiring on motor-cars and aeroplanes, and in similar situations where they are likely to come in contact with oil.

Tapes for fire-resisting purposes are made from specially prepared cloth, which is fire-proofed by a process which comes under the category of a cloth-finishing process. One of the most effective methods consists in fixing an insoluble tin salt in the fibres of the cloth. While this results in the production of a fabric which is not only non-ignitible but which is unaffected, as regards its fire-resisting properties,

by moisture or even by washing, it remains for the cable-maker to adapt it to the purpose of cable covering by rendering it impervious (or partially so) to the passage of air or gases, so that the passage of products of combustion or volatilisation of the underlying material, *e.g.*, rubber insulation, shall be prevented or at least impeded.

This is accomplished by treating the prepared cloth with a fire-proof paint or compound. After the tape is applied to the cable, and during the subsequent application of fire-resisting braids, which are almost invariably the main component of fire-resisting coverings, a further serving of fire-proof paint or compound is applied, so as to fill the interstices of the braid. Apart from actual cable manufacturing processes, this tape is often used for taping cables *in situ*, although asbestos in the form of selvedge tape or webbing is more convenient to apply, because of its greater pliability. It is, however, peculiarly hygroscopic, and needs heavily coating with asbestos paint in order to counteract this, and to make it relatively impervious to air and gases.

Coarse jute (Hessian) tapes are chiefly used over, and sometimes under, armourings of steel tape or wire in large underground cables, in place of jute yarn lappings. They give the advantage of a rather more uniform covering, and are rather more effective in enclosing a complete layer of compound than yarn lappings, and give, therefore, a rather less pervious covering. A heavy Hessian with a fairly open mesh is generally to be preferred, because, although more pervious in itself, it is more amenable to being filled by the molten bituminous or pitch compound which is invariably applied under and over it during its application to the cable, the open meshes forming a key for the compound. The Hessian is, of course, as in the case of bitumen tape, impregnated with bituminous compound before cutting into tapes.

Red lead paint or compound is sometimes used for the preparation of Hessian in place of the bituminous compound, and in addition to being an excellent preservative, the distinctive colour permits of it being utilised for purposes of identification of cables in the ground, *e.g.*, distinguishing high-pressure from low-pressure mains.

COMPOUNDING (BITUMINOUS AND PITCH COMPOUNDS)

The base constituent of the compounds commonly used for preservative purposes on lead sheaths, armourings and certain fibrous coverings in underground cables is either Gas Pitch (otherwise known as Coal Tar Pitch) or Petroleum Pitch, or a mixture of both, sometimes with a proportion of one or other of the solid bitumens. The same remark applies to the saturation of the braided coverings of aerial cables, and the preparation of tape fabrics. Other ingredients, used in various proportions, are resin, resin oil, creosote oil, anthracene oil, and certain varieties of mineral oil, the function of these being to " temper " the pitch base of the compound. (Reference is made under Manufacture, Vol. II, to the considerations which govern the choice and proportioning of these materials in a compound.) With the exception of gas pitch, creosote oil, and anthracene oil, the above-mentioned materials have been referred to earlier in the preceding chapter.

Gas pitch is a by-product obtained in the manufacture of coal gas. Coal is heated in retorts, and the products of distillation may be roughly divided into three classes :—

(*a*) Gases.
(*b*) Aqueous liquor, containing ammonia and other substances of a basic character.
(*c*) Tar, the residue of which consists of pitch, or ultimately, coke.

The tar is a black viscous liquid of complex chemical composition, containing substances capable of conversion into valuable products, notably, many which form the basis of the dye industry ; in fact, in this connection the history of the coal-tar industry borders on romance.

Subjected to fractional distillation, the substance yields more than one product of use to the cable-maker, amongst which may be mentioned toluol (used as a solvent in rubber manufacture), creosote oil, and anthracene oil ; the residue consists of gas pitch.

It will be readily appreciated that the main objective of the distillation processes is to obtain the valuable materials above referred to, and the matter of the quality of the residual product—the pitch—is a comparatively remote consideration. Some slight modification has occurred of recent years in this situation owing to the great demand which has arisen for pitch for road-making purposes, but in the main the question of uniform quality of pitches must, in the nature of things, remain a subsidiary one.

The hardness, ductility, and other physical properties, and the composition of gas pitch varies considerably according to the particular coal treated and the degree to which the distillation is carried ; for instance, if the temperature at which distillation is stopped is comparatively low, a product of correspondingly low softening-point will be obtained ; on the other hand, if the distillation is carried to an advanced stage, a high softening-point pitch of a hard, brittle—almost friable—nature, containing a considerable quantity of free carbon, will result.

The hard pitch breaks readily in brittle fashion with a conchoidal fracture, and possesses a dull greyish black colour. The softer varieties are blacker and more glossy in appearance, and while being more ductile, will also break with conchoidal fracture under a sufficiently sharp blow, this being a characteristic of all pitches, solid bitumens, etc.

Gas pitch is a notable example of the class of substances known as semi-solids ; even the harder grades will show a tendency to flow on being left for an extended period at ordinary temperature. This phenomenon is shown by the sharp edges gradually disappearing and the mass sooner or later spreading over a large area.

Such substances possess no definite melting-point, the nearest equivalent being what is commonly called the " softening " point, this being determined by various methods, all of which are of an arbitrary character, and consequently producing variable results.

Consistent comparative values are, however, easily obtainable by the cube method described in connection with bituminous substances under Testing. The

heterogeneous character of the hard varieties is shown by the irregular manner in which the cubes lose their original shape, and this is especially noticeable in cases where the distillation has been carried too far, with the result that the product is partly coked.

The grading of pitch in trade circles for the purpose of commercial valuation is generally based on a crude test known as the twisting test. This is not standardised, and the *modus operandi* varies considerably according to different authorities. In a general way the method may be described as follows :—

A piece of pitch is either moulded or cut to a suitable size, say, $2'' \times \frac{1}{2}'' \times \frac{1}{2}''$, and suspended in a beaker of water which is heated at a constant rate. The sample is withdrawn at intervals, and the temperature at which it may be fairly easily twisted without breaking is recorded as the twisting-point.

References to the various methods adopted for determining the softening-point of pitch, together with a method suggested by Spielmann and Petrie, will be found in the *Journal of the Society of Chemical Industry*, vol. 38, No. 6, p. 68, T. *et seq.*

Other tests which are useful for checking regularity of supplies are specific gravity and ash, which are carried out in the usual manner.

Varieties of pitch possessing a high softening-point, as previously stated, invariably contain free carbonaceous matter, and as this is usually of a gritty nature, its presence in the final product is undesirable. The presence of carbonaceous matter in soft and medium grade pitches is indicative of a " cut-back " product, *i.e.* the softening of a hard pitch by the addition of certain distillation products, a procedure sometimes adopted when distillation has been carried too far.

Creosote Oil is generally understood to relate to the product obtained by the distillation of coal tar, although certain varieties are also obtained from wood tar. The former product usually consists of a mixture of the fraction distilling between 230° and 270° C. and the residual carbolic oils ; it is of very complex composition, possesses a distinctive odour, and is characterised by its high specific gravity (1·02 to 1·08) compared with other oils.

The creosote oil of commerce is usually of thin consistency, brown in colour, and the composition varies in character according to the source of supply. It finds a variety of uses in the arts and manufactures, but one of the best known, and the one in which the cable-maker is most interested, concerns its antiseptic properties, which have been ascribed to various constituents, and which render it of great value for preservative purposes.

The presence of naphthalene, which crystallises out at low temperatures, whilst not being an objectionable constituent, should not be present to such an extent that separation occurs above 60° F.

Other tests specified by various purchasers, according to the particular purpose for which it is to be used, are maximum (and sometimes minimum) percentages by volume distilling below a certain temperature, minimum percentage of tar acids, specific gravity, and moisture content.

Anthracene oil (green oil) is the fraction of coal tar distilling above 270° C. It contains many valuable substances (chief of which is anthracene, an important

basic product of the dye industry) which crystallise out on cooling, and these substances are of course removed before the oil is received by the cable-maker.

COMPOUNDING (OZOKERITE AND WAX COMPOUNDS)

The origin and production of ozokerite has been dealt with earlier in this section. It may be regarded as the standard preservative material for application to the tape and braid coverings of rubber-insulated wires and cables. Its outstanding characteristics, viz., non-crystalline structure, plasticity, and comparatively high melting-point render it particularly suitable for this purpose, permitting ready saturation of the braid by simple immersion in the molten material, good filling of the interstices, and flexibility in the finished state, *i.e.* freedom from tendency to crack when the cable is bent. The latter property, as well as the facility for taking a smooth polish, is due to the peculiar plastic waxy nature of the material.

For the preservation of the underlying rubber the matter of a smoothly polished finish is important, as the ozokerite is thereby distributed over the surface so as to form a fairly continuous film which will—to an extent not usually realised—exclude air and moisture. It also facilitates the drawing of insulated wires into conduit tubes.

Various cable-serving waxes having paraffin wax as a basic constituent are often used to substitute ozokerite mixings.

The use of paraffin wax alone is precluded on account of its low melting-point and crystalline structure ; consequently admixture with small proportions of waxes possessing a relatively high melting-point, such as carnauba, montan, Japan wax, etc., is fairly common practice. These waxes have already been referred to under Impregnating Compounds.

Rosin is also used to some extent in these ozokerite substitute compounds, but as it has a deleterious action on the insulation its use is to be deprecated. This matter is referred to later, under Causes of Deterioration (Vol. II).

For certain types of " weatherproof " finish such as aerial cables and other types of cable exposed to severe weather conditions, admixture is made with petroleum pitch, wax tailings, and other bituminous substances.

Suitable blending in order to obtain specific properties is a matter of experience and experiment, and a knowledge of the exact purpose for which it is required ; for example, it is fairly common practice, especially in America, for the final serving or compounding process to be carried out in two operations, viz., " saturating " and " finishing." The former aims at thoroughly saturating the braid, and consequently a compound with comparatively low viscosity and melting-point is desirable. In the case of the latter process a more flexible compound capable of taking a good polish is required.

A combination of saturating and finishing waxes is sometimes employed, in which case the " serving " is carried out in one process ; naturally the result is not so effective.

A rather serious drawback to certain of the " saturator " and " finisher " types of waxes, judged by the numerous samples which have come under the notice of the author, is the fact that they will not withstand continuous heating without becoming physically changed in character ; this change usually takes the form of gelatinisation (partial or complete), or separation of the constituents.

The required colouring of ozokerite or substitute waxes may be obtained by means of suitable pigments or wax-soluble dyes.

Red-lead compound is used as a preservative compound on certain types of aerial cables, a notable example being the Post Office P.B.J. wire referred to under Conducting Materials, p. 53. In this case the conductor is insulated with two layers of impregnated paper, lapped and braided with cotton yarn, both cotton coverings being impregnated with red-lead compound. The approximate composition of the compound is red lead 72 per cent., linseed oil 16 per cent., and paraffin wax 12 per cent. The cable is finally passed through a bath of paraffin wax in order to produce a smooth and glossy surface.

III. DESIGN

CHAPTER VI

NOMENCLATURE AND MECHANICAL PRINCIPLES

Owing, no doubt, to the manner of and circumstances connected with the evolution of the cable industry, the nomenclature commonly employed is somewhat loose, and frequently inconsistent. For example, the term " core " in submarine telegraph cable manufacture always related to the completely insulated conductor and defined the state of the cable prior to the application of protective coverings. The extreme importance of obtaining sound tests at this stage, before proceeding with the mechanical protection of great lengths of " core," doubtless accounted for the definite application of the term in connection with submarine practice.

In electric light and power cable manufacture, however, this reason for conciseness in the use of the term disappears, because, for example, in the case of fibrous insulated cables it is necessary to lead cover them before the main factory tests can be applied.

It therefore comes about that not only in the cable works but also in specifications, etc., the word " core " is sometimes used to indicate the conductor—as instanced by the frequently encountered expression " the core is to be insulated with," etc.—and sometimes as referring to the insulated conductor—for example, " the cores to be laid up together," etc., or " the insulated core to be sheathed with " etc.

In what follows the word " core " will be used to indicate an insulated conductor.

Again the word " strand " is sometimes used to indicate a stranded conductor, and sometimes to refer to a single member of a stranded conductor, *e.g.*, " each strand to be coated," etc., or " each layer of strands," etc.

The word will be used herein in the latter sense.

Expressions such as " twinning " and " pairing " are sometimes regarded as synonymous and used indiscriminately in ordinary work, but for the purposes of telephone cable manufacture the former term is used for the twisting together of the singly insulated wires and the latter for the twisting of two " twinned " conductors together to form a four-core (or " quad ") member of the cable. At the same time a telephone cable in which only twins are involved, and " quads " are not used, is described as an " n-pair " cable.

The term " pairing " will only be used in the sense above noted, *i.e.* to indicate the twisting up of cores already " twinned."

The word " lay " should, strictly speaking, be used to denote the ratio which the pitch length of a convolution bears to the pitch diameter of components or members (*e.g.*, strands, cores, armour wires, or lappings) spirally laid up in a cable.

It should therefore be expressed in terms of n times the pitch diameter of the components in question.

It is, however, quite common to use it to indicate the pitch of convolution or

" length of lay," *e.g.*, the cores of a cable may be specified to be laid up with a twelve-inch lay.

It is actually defined in this latter sense in the B.E.S.A. Specification No. 7, 1922, entitled " British Standard Specification for Dimensions of Insulated Annealed Copper Conductors for Electric Power and Light " (p. 7, Clause II), as follows :—

" The term ' lay ' denotes the pitch of the helix formed by any individual wire in a stranded conductor or by any individual core in a multicore cable."

It is also used in indicating the direction of spirality of members, *i.e.* a " right hand " or " left hand " lay.

These inexactitudes are so common, and withal, so convenient, that it is perhaps better to accept them as conventional expressions than to suggest more accurate but more cumbrous ones.

The word " sheathing " is commonly used as both noun and verb, but it is obvious that in this instance the matter is one of philological inexactitude rather than one affecting distinction between assembly operations or component parts of the cable, and that any possible confusion would be prevented by using the verb " to sheathe " and employing the word " sheath " as the noun.

This will be adopted in what follows.

A further instance of looseness in nomenclature is the indiscriminate use of the word or suffix " proof." It will be evident from a moment's consideration that it is highly desirable to differentiate between proofness and resistance to, for example, water, fire, oil, acid, etc.

For instance, a sound lead sheath may clearly be called " waterproof," but an asbestos covering, when applied over a combustible dielectric such as vulcanised rubber, can only be regarded as " fire-resisting " and not " fireproof," because the resistance to burning due to the use of such covering is only a matter of degree, depending on the relative bulk (*i.e.* radial thicknesses) of the combustible and non-combustible components of the cable. In other instances proper nomenclature depends on the conditions under which a cable is to be used, as well as on its composition. For example, a varnished cambric dielectric may not suffer damage to its general properties by being immersed in oil, even should the oil penetrate between its layers ; but if varnished cambric tapes, etc., are applied over a dielectric material such as rubber, damage to the rubber is simply a matter of degree of resistance to penetration, or percolation between layers. In the latter case the varnished cambric only affords an oil-resisting covering, whereas in the former case it virtually constitutes an oil-proof dielectric.

These instances are perhaps sufficient for the purpose of pointing out that we have, in cable manufacture, insulating and covering materials, some of which are " proof " against certain deleterious influences, and others which, while in themselves " proof," cannot be so regarded when used to protect other (susceptible) materials.

It follows that the latter should strictly be called " resisting " coverings, and this distinction will be made in what follows.

Allied to the foregoing is the broader matter of the distinction which should be drawn between the terms " insulated " and " covered," which are often loosely employed in specifications. The lack of distinction is probably largely due to the influence of American practice. In earlier days " Underwriter's " wire was used under conditions which entailed reliance on treated cotton coverings for insulation, and even to-day the " National Electrical Code " of America describes " weather-proof " and " slow-burning " wire coverings as " insulation " or " insulating coverings."

Concise differentiation between " insulated " and " covered " is of course somewhat difficult from the point of view of pure definition, because for practical purposes the conditions of use would also have to be closely defined, and the desirability of this is open to question. For the purposes of this work the term " insulated " will be used to indicate that the conductor has a dielectric of one of the three or four main types possessing definite and permanent insulating properties, while the term " covered " will be used in connection with other types of coverings which—while they may possess appreciable insulating properties—are susceptible to conditions to which insulated conductors are ordinarily exposed, and liable to have whatever insulating properties they possess more or less impaired thereby. For example, cotton or asbestos " covered " wires would fall under the latter (susceptible) classification, whereas vulcanised rubber " insulated " wires would not.

MECHANICAL PRINCIPLES OF DESIGN

In dealing with matters of mechanical design it is perhaps advisable to review elementary principles, because they are liable to be lost sight of by reason of the familiarity of cable users with general details of construction and assembly. A wider appreciation of the fundamental reasons governing the matter would appear to be highly desirable.

The ordinary conditions of manufacture of long lengths, and of transport, handling, and fixing conditions, always necessitate some degree of mechanical flexibility in cables. The result is that components of cable construction have to be either to some extent selected for their mechanical properties, or alternatively formed and applied in such a way as to comply with the mechanical requirements of the finished cable.

In conductor materials, for instance, the ductility of the metal provides for a certain amount of flexibility in the cable unless its sectional area is too great to afford the necessary *degree* of flexibility, in which case it is suitably subdivided, and its component parts assembled in spiralled form as a stranded conductor.

In some dielectric materials, such as rubber and vulcanised bitumen, which are capable of being applied in a continuous and homogeneous form, elasticity or resilience provides the necessary flexibility, while in the case of complete metallic sheaths, sufficient ductility has to be secured by using lead or an alloy thereof, no other metal being sufficiently ductile for the purpose.

In all cases where the properties of ductility, elasticity, or resilience are utilised, flexibility is attained by distortion of the component parts in which these properties are provided.

When we come, however, to materials which do not possess—or possess to an insufficient degree—these properties of ductility or elasticity, the various components have to be assembled and applied in spiral form, the attainment of flexibility being then dependent on relative movement of the various parts, *e.g.*, paper strips sliding upon one another, or the individual spirals comprising a stranded conductor, or an armour sheath, moving in relation to one another—in other words, on displacement rather than on distortion.

As this spiral application bears a fundamental relation to other than purely mechanical features of design, it may be desirable to pay brief attention to the

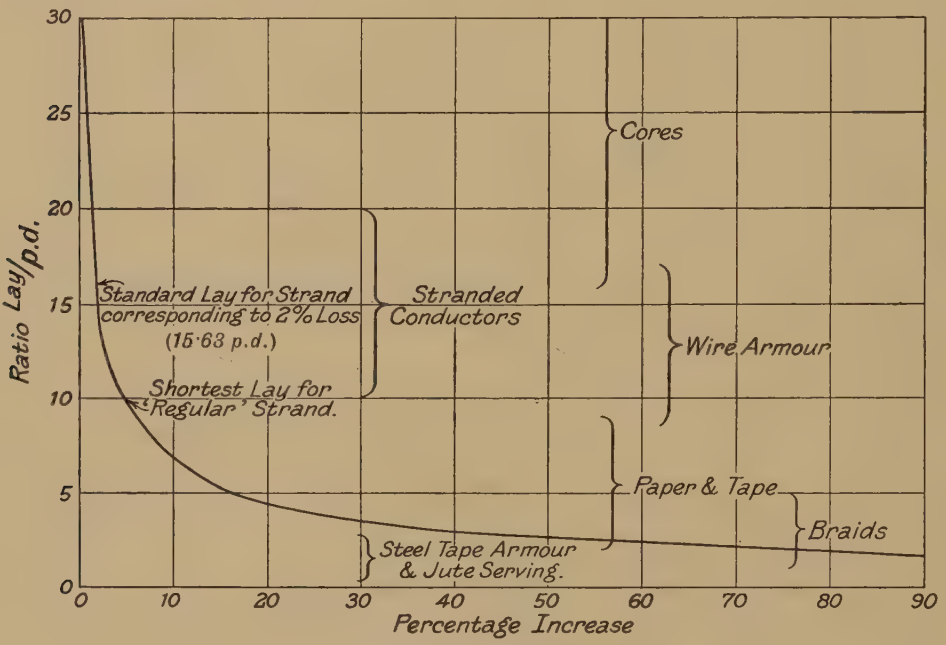

Fig. 16.—"Lay" Curve.

accompanying "lay" curve, Fig. 16, which illustrates percentage increase of length over axial length due to spirality at various values of length of "lay" expressed in terms of pitch diameter of convolution. Equally, of course, it represents percentage increase of weight, and—in the case of conductor or armour strands—of resistance. Moreover, a reciprocal curve would represent degree of relative movement of a given point on a convolution entailed by a given degree of bending of the cable, and therefore in an elementary sense—in so far as simple resistance to movement is concerned—would represent a measure of flexibility.

While approximately true for the case of a simple spiral, so many disturbing

factors enter the complex assembly of a cable that the reciprocal curve above mentioned would be only of value as an intelligent conception of the general bearing of " lay " on flexibility.

The lay curve is marked to indicate the values of percentage increase which ordinarily apply to the various spirally applied components of insulated cables. It will be seen that the longest lays are those used in assembling the insulated cores of multicore paper cables. The relative movement is therefore greatest in these components, and such movement is plainly visible when winding a short length of multicore paper cable on or off a drum, the cores at the cable end being seen to alternately advance and recede as the winding proceeds ; and if the stranded conductor is fairly large the same action may be seen occurring independently in it, though to a much smaller degree, because of its shorter length of lay. In the case of a long length the effect is only visible at the beginning or end of a winding operation, the lateral movement being taken up transversely when end play is restricted by lateral resistance.

An important elementary principle of design is the balancing of the mechanical stresses entailed by this spiral application and assembly of component parts,* and a brief reference to experiments carried out by the author to demonstrate the necessity of this may not be out of place.

It may be postulated that in a common construction of cable, such as a 3-core, bitumen-sheathed wire armoured cable, the component parts constitute a number of spiral members in which, as indicated above, the relation between length of lay and pitch diameter vary considerably.

The lengths of lay of the stiffer components—the insulated cores and the wire armour—are great in proportion to the pitch diameter of the spirals they represent, while the converse is the case in the softer components, such as the tapes and fibrous lappings.

It is therefore of interest to know what happens to disturb the stiffer spirals when subjected to tensile stress, this being a condition which almost invariably arises in installation or permanent use, or (*e.g.*, in a pit shaft) in both, the short lay components being innocuous in this respect.

If we take a single spiral of steel wire having proportions of the order usually employed in ordinary wire armouring, say, lay $= 15 \times$ pitch diameter, fixing one end and leaving the other free to move, and apply a tensile stress, we find that the spiral tends to unwind ; whereas if a spiral of the same material but having different proportions as regards spirality, say, lay $= 0{\cdot}5 \times$ pitch diameter (as in spiral wire armour), is subjected to the some conditions of test, we find that it winds up instead of unwinding. In other words, the free ends of the spirals rotate in different directions according to the relation between their diameter and the pitch of their convolutions or length of lay.

The actual direction of rotation depends on whether the spiral is made with a right hand or left hand lay, as follows :—

* Old Government specifications commonly contained—and some still retain—a stipulation that the cable to which they referred should be free from any tendency to twist, and should " lie dead " in the finished state.

* Direction of lay of spiral.	Direction of rotation of spiral.	
	Length of lay, say 20× P.D. or greater.	Length of lay, say 0·5× P.D. or less.
Right hand . . .	Clockwise	Contra-clockwise
Left hand . . .	Contra-clockwise	Clockwise
	† (Unwinds under tensile stress)	(Winds up under tensile stress)

It is, of course, well known that the general broad practice in building up a cable is to reverse the direction or "hand" of lay at each successive operation.

The following diagram, Fig. 17, selected as an example from a number of experiments on different types, gives the results of actual tests, and illustrates the necessity of taking into account the relative flexibilities of components and the proportion of long and short lay operations in the mechanical design of a cable.

The cable in this particular case was a 3-core 7/·028-in. tough, rubber-sheathed, taped, and double wire armoured (·048 in.) cable, such as is frequently used in connection with pit sinking work. The direction of lay was reversed at each manufacturing operation, commencing with the laying up of the cores with a left hand lay in opposition to the right hand lay of the stranded conductors.

Tests were carried out on samples 5 ft. 4 in. in length, between each manufacturing operation entailing spiral application, the *modus operandi* being to submit them to a tensile stress in a testing machine, the lower end of the sample being anchored and the upper end left free to rotate. The values of longitudinal extension and the corresponding angle of rotation were noted at half-minute intervals during the whole cycle of extension and retraction (the latter indicated by dotted lines) and plotted as shown in the diagram on the opposite page.

It will be noticed that, in general, the constituent layers tend to behave in a similar manner to the simple spirals above referred to. (This was also confirmed on spiral wire armoured lengths of similar cable.)

The unwinding effect on the sheathed laid-up cores is considerable and is not balanced by the tapes.

The first layer of armour overbalances the preceding assembly, its rigidity being considerably greater than that of any of the other constituent layers, and

* The generally accepted definition of a right hand lay is that the twisted or stranded component runs away from the observer from left to right. Conversely, in a left hand lay it runs from right to left.

† It will be evident from this behaviour that the direction of rotation reverses at a certain critical point in the relation of pitch to diameter when the spiral is sufficiently extended. Most cable-making conditions are, however, clear of this complication.

being applied with a right-hand lay rotates the whole in a clockwise direction when tensile stress is applied.

The second layer of armour, being applied with a left hand lay, gives a contra-clockwise effect under tensile stress, sufficient to counterbalance the net effect of the other components, so that Curve E, representing the final condition, is a vertical line, indicating that the assembly is balanced and that the cable will "lie dead" under any ordinary condition of installation entailing tensile stress; any further

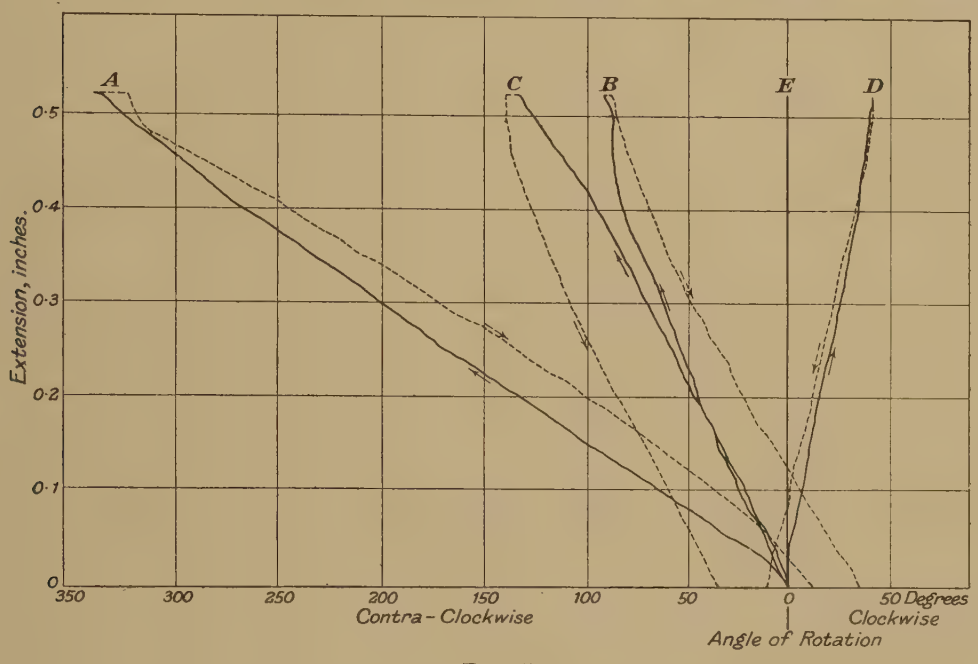

FIG. 17.

Curve A relates to test on rubber-sheathed, laid-up cores						L.H. lay
„ B „	further test after application of				1st tape	R.H. „
„ C „	„	„	„	„	2nd tape	L.H. „
„ D „	„	„	„	„	1st layer of wire armour	R.H. „
„ E „	„	„	„	„	2nd layer of wire armour	L.H. „

Curves A, B, C, and D each form a sluggish kind of hysteresis loop.

coverings, such as jute lappings or Hessian tapes, will have no effect, being practically always applied in two layers in reverse directions.

Braids may be used singly, as they constitute a covering which is balanced in a spiral sense; in fact, it is always desirable to apply protective coverings—whether of metallic or fibrous material—to very flexible cables in this form.

Turning to the matter of flexibility *qua* flexibility, it may be useful to point out the bearing of conductor design on the purposes for which the insulated cable is intended.

The common conception of flexibility is pliability, or ease of bending to a small

radius, and it is not usually appreciated that there are many conditions of use in which this kind of flexibility is of comparatively small importance.

The matter of degree and character of flexibility may be briefly surveyed as follows :—

(*a*) Extreme pliability, required for conditions where very frequent movement is entailed, as in certain automatic apparatus. As very small currents are usually involved in such cases, the lines of manufacture of telephone cord can be followed, *i.e.* by wrapping the conductor in the form of tinsel strip over a centre of cotton yarn.

(*b*) Moderate pliability, such as is demanded for electric lighting pendant and similar purposes. The same order of flexibility is usually demanded in " dynamo flexibles " and heavier types of flexible connecting cables for special purposes.

This requirement is fulfilled by " bunching " or twisting fine wires together.

(*c*) Flexibility sufficient for purposes of easy installation, as distinct from conditions entailing repeated bending during the life of the cable. This degree of flexibility may be attained by simply decreasing the size of wire employed for the individual strands of the conductor, and correspondingly increasing the number of strands to make up the required area. Such cables are usually stranded in " regular " formation (see Properties of Stranded Conductors, p. 146) of wires about 0·036 in. or 0·044 in. diameter, *i.e.* between the fine sizes used for ordinary flexibles and those employed for standard stranded conductors.*

The mistake is commonly made of specifying and using this form of conductor in portable or trailing cables. A moment's consideration will show that it is eminently unsuitable for this type of duty.

Even if the lay of the various layers of strand is uniform, so that the same amount of relative movement of all the wires is provided for, the frictional resistance to movement will vary from place to place, and as there is little lateral stiffness in the component strands, they cannot extend uniformly nor retract completely when the cable is subjected to severe bending or unbending.

Consequently they tend to buckle or kink, and the cable soon assumes a wavy appearance, and breakage of wires ensues through the required movement due to bending being concentrated on the kinks.

(*d*) Flexibility combined with non-kinking properties. This is a variety of flexibility which is highly desirable in all forms of portable cables used for power and trailing purposes.

For such work a certain degree of pliability can be sacrificed without detriment in order to attain resistance to permanent set under bending and torsional stresses, and this is effected by introducing a certain lateral stiffness in the design.

It may be noted that the same general requirements apply to certain special

* This type of stranded conductor dates back to the early days of electric lighting, when it was Admiralty practice to allow one wire of 0·036 in. diameter (20's S.W.G.) for every lamp. Consequently if a main or distributor had to supply, say, eighty lamps, the size of conductor specified was 80/20's S.W.G. It is interesting to note that this form of conductor is often specified at the present time as " Admiralty stranded," although as noted above its construction does not differ from ordinary stranding.

types of cable, such as flexibles for use with electric irons, field telegraph cables, etc. In these cases—where conductivity is not very important—the requirement may be filled by the introduction of a few steel wires in the conductor.

In the case of a portable power cable, however, in which conductivity is of paramount importance, the case is met by " multiple stranding " the conductor, *i.e.* subdividing the stranded conductor into a number of separately stranded multiples, the requisite balance between pliability and lateral stiffness being attained by choosing sufficiently fine wire for use in building up the multiples.

In a well-designed multiple-stranded conductor, an individual strand cannot—by simple bending of the whole cable—be displaced from the multiple of which it forms part, and as each multiple is independent so far as lateral movement is concerned, it not only offers a minimum of frictional resistance to relative movement due to bending, but possesses sufficient lateral stiffness to accomplish practically complete retraction without buckling when the bend is removed or reversed. At the same time an ample degree of transverse flexibility is afforded by the multiple strand construction.*

The desirability of employing multiple stranded conductors in trailing and " jumper " cables being obvious, it is interesting to note that the tough rubber sheath which is usually applied to these cables is an appreciable aid in the same direction, by reason of its elasticity in a tensile sense, and in a transverse sense by its resistance to collapse, both features affording flexibility while resisting deflection or distortion.

There are a number of factors in manufacture which militate against mechanical perfection in cables, which have to be borne in mind when considering design. For example, variations of lay from place to place may arise from the effect of one operation on the assembly up to that point—such as the effect of applying a stiff armour over comparatively flexible laid-up cores—and may lead to kinking trouble under conditions of bending, expansion, etc.

In general, it is important to remember that every movement of a cable throughout its life, whether due to winding and rewinding during manufacture and installation, or to expansion and contraction effects which may arise in use, should be uniformly distributed over as great a length of the cable as possible, because, as noted already in the case of flexible conductors, any movement to which a cable is subjected will tend to concentrate on, and develop a kink of any kind which may already exist.

The flexibility of components of a cable should bear some relation to that of the least flexible component; for example, it would be useless and wasteful to use a very flexible conductor in a lead-covered cable, because the ductility of the lead tube would in such case be the limiting factor in the flexibility of the finished cable.

* The B.E.S.A. Report on Insulated Copper Conductors (No. 7, 1922) simply specifies the number and diameter of wires for flexible conductors, and indicates some of them as " For trailing cables and similar purposes." Multiple stranding is not indicated. Reference is made later to American standards for multiple or " rope "-stranded conductors.

To go to the other extreme, in the case of a shaped conductor multicore paper cable, the conductors are the limiting factor.

In this connection, it probably occurs to few cable users that shaped conductors in a multicore cable are undesirable from the mechanical point of view, for the reason that—contrary to the case of a circular stranded conductor—one complete twist per length of lay has to be put into the cores in laying them up.

As a permanent set cannot be put into the shaped strand in doing this, torsional stresses are " tied up " in the laid-up cores, and a tendency to untwist permanently exists.

In succeeding manufacturing operations each bending and unbending which occurs in winding on and off drums tends to make the cores move in relation to one another, and if these residual torsional stresses are insufficiently controlled and allowed to react at the same time, the relative positions of the cores become distorted.

Clearly, under such conditions, the number of times a cable may be bent is strictly limited, and for such limit to be reached before the cable gets through its manufacturing operations is not unknown. Cases have also been encountered where the limit has been arrived at in laying, suspending, or other process of installation.

With regard to the provision of mechanical strength to withstand tensile stress, it is seldom that the insulated conductors themselves are required to fulfil this function, except in cases of quite small conductors and light weights, and temporarily, during drawing-in, etc., in the case of heavy unarmoured cables. When cables are carried overhead on pole lines they may, in the case of small multicore cables such as V.I.R. telegraph, telephone, and lighting cables, be constructed with a steel centre to take the stress, but heavier types of power cables are usually supported on suspenders from steel catenary wires and thus relieved from appreciable tensile stress. In the case of cables hung vertically, as in pit shafts, wire armour usually fulfils the double function of mechanical protection and the provision of tensile strength.

Radial strength or resistance to external damage by blows or crushing stresses is chiefly provided by various forms of metallic armour, or in the case of unarmoured cables, such as trailing cables, by tough rubber sheaths. There are, however, other aspects of radial strength which call for internal reinforcement in various ways. Such internal reinforcement may be required to counteract stresses which are entailed by manufacturing operations in addition to those in the nature of mechanical damage to the finished cable ; for example, in the case of a twin or multicore cable, mechanical stresses are entailed when the cores are twisted up together, which act in a radial sense on each of the individual cores, and are concentrated on the line of contact between them.

At a later stage of manufacture, the application of outer coverings, *e.g.*, armour, set up stresses which act in a radially inward direction on the completely assembled cable, and although jute bedding or stout Hessian tapes are usually provided to cushion the pressure of the wires or strips, some of the radial pressure due to their application is more or less bound to be transmitted to the cores.

When the dielectric of the cores is of small thickness or is composed of a comparatively weak material, having, as in "solid" * vulcanised bitumen cable, no mechanical protection over the core insulation, there may be some risk of deformation of the dielectric wall due to these manufacturing operations. These tendencies may be counteracted by the provision of a web or "cradle" † made of similar or stronger material suitably shaped to receive the insulated cores. Fig. 18 illustrates the application of this cradling principle to a twin solid bitumen cable. The cradle not only affords a wide base of support for the dielectric of each conductor in place of the simple line of contact above referred to, but also affords a reinforcement against the radial stresses due to subsequent armouring or covering operations on the assembled cable.

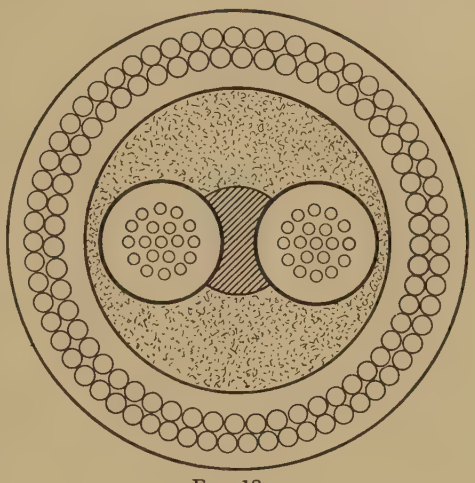

Fig. 18.

The cradling or "cracore" principle is often applied to multicore tough rubber sheathed types of cable, although the object in these cases is to meet the exigencies of use rather than those of manufacture; for instance, in trailing cables the function of the rubber cradle is to cushion the comparatively lightly insulated cores against the effect of blows or concussion such as frequently occur in mining work, due to falls of rock or stone.

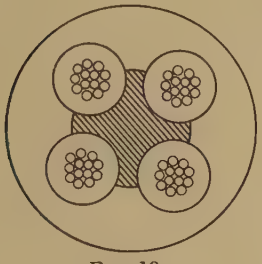

Fig. 19.

In the ordinary construction such effects are cushioned to a proportionately greater extent between the exterior of the cable and the cores than between the comparatively hard and thinly covered cores themselves; so that the insulation between cores is rather more easily burst through under fall conditions than the insulation plus sheath. The interposed cradle corrects this unbalance in the mechanical design. Fig. 19 shows a 4-core coal-cutter trailing cable constructed on this "cracore" principle.

Again, in the case of a "jumper" cable, the rubber cradle forms a pliable centre, definitely spacing the cores apart; and this, together with the small movement secured by the spirality of the insulated cores and their multiple-stranded conductors, and the properties of the tough rubber sheath already referred to, constitute an excellent combination of pliable and non-kinking properties for a case which demands a maximum of both. Fig. 20 shows a 10-core jumper cable so constructed.

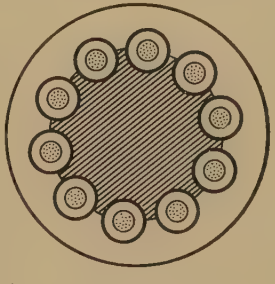

Fig. 20.

* Patent No. 8238/1906. Beaver & Claremont. See page 255.

† Patent No. 9523/1911. Beaver & Claremont.

CHAPTER VII

CONDUCTORS

PROPERTIES OF STRANDED CONDUCTORS

Rules as to the limit of size of solid conductors, *i.e.* above which conductors for insulated cables have to be stranded, vary in different countries, and also, in some countries, according to the purpose for which the cable is to be used.

In Germany the Rules of the Verband Deutscher Electrotechniker (V.D.E.) state that conductors in cable insulated with rubber (either pure or vulcanised) having a sectional area greater than 16 sq. mm. (approximately ·178 in. diameter = ·0248 sq. in. area) must be stranded. In paper lead-covered cables the limit of size for solid wires was formerly 10 sq. mm. (approximately ·140 in. diameter), but in the latest edition (1923) of the Rules, this has been increased to 16 sq. mm., making it uniform with the limit for rubber cables.

In other countries where stipulations on this point are made they chiefly relate to wiring installation work and not, as in Germany, to main cables.

The object in the German Rules is apparently to prevent mechanical design being sacrificed to cheapness of production, whereas in the Rules which apply in other countries it would appear to be chiefly to suit the wires to the conditions of installation in buildings, etc., reference being made only to small wires.

For example, in Great Britain the Regulations for the Electrical Equipment of Buildings (formerly known as the I.E.E. Wiring Rules) stipulate that all insulated copper conductors having a greater cross sectional area than that of a 16's S.W.G. (·064 in. diameter) wire must be stranded ; and naturally the Rules of the various Fire Offices and Electricity Supply Authorities follow the Regulations for the Electrical Equipment of Buildings. Lloyd's Rules for Shipwork, however, specify No. 14's S.W.G. (0·80 in. diameter) as the size above which conductors must be stranded.

Australian Fire Underwriters' Rules, while generally following the Regulations for the Electrical Equipment of Buildings, specify 14's S.W.G. as the limit for solid wires in insulated conductors.

In America the National Electric Code (N.E.C.) Rules specify that for car wiring all conductors must be stranded, and for ship wiring (marine work) all conductors larger than No. 12 B. & S. (·0808 in. diameter) must be stranded, but apparently place no limit on wires for general inside work, and sizes up to No. 6 B. & S. (·162 in. diameter) for single and No. 10 B. &. S. (·102 in. diameter) for twin are commonly used.

In Canada the Rules of the Hydro-Electric Commission of Ontario, while more or less following N.E.C. lines, specify that for general installation work sizes larger than No. 12 B. &. S. gauge must be stranded.

Standard practice also varies in different countries with regard to the composition of ordinary stranded conductors to comply with given values of effective area, as illustrated by the following Table.

TABLE VIII

Stranded Conductors

Standard (nominal) area of conductor.			Composition of strand.	Number of wires in strand.				
					Minimum specified by V.D.E. rules.			
British sq. ins.	American circular mils.	German sq. m/m.	British.	American I.E.E. standards.	Rubber, braided.	Paper or rubber, lead covered. Without test wire.	Paper or rubber, lead covered. With test wire.	Multi-core.
..	20,800	..	..	7	..	..	..	..
·0225	..	..	7/·064″	..	..	..	..	..
..	..	16	..	..	7	1	3	1
..	..	25	..	..	..	7	6	7
·0400	..	..	19/·052″	..	..	..	..	..
..	66,400	..	..	7	..	..	..	..
..	..	35	..	..	19	..	..	..
·0600	..	..	19/·064″	..	..	..	..	..
·0750	..	..	19/·072″	..	..	..	..	..
..	..	50	..	..	..	..	..	19
·1000	..	..	19/·083″	..	..	..	..	..
..	133,000	..	..	19	..	..	..	..
..	..	70	..	..	..	19	13	19
·1200	..	..	37/·064″	..	..	..	..	..
..	..	95	..	..	..	..	..	..
·1500	..	..	37/·072″	..	..	..	..	..
..	212,000	..	..	19	..	..	..	..
..	..	120	..	..	37	..	..	..
·2000	..	..	37/·083″	..	..	..	..	..
..	..	150	..	..	..	..	18	37
·2500	..	..	37/·093″	..	..	..	..	..
..	..	185	..	..	..	37	26	..
·3000	..	..	37/·103″	..	..	..	..	..
..	400,000	..	..	37	..	..	..	..
..	..	240	..	..	61	..	29	..
..	500,000	..	..	37	..	..	..	..
·4000	..	..	61/·093″	..	..	..	..	..
..	600,000	..	..	61	..	..	..	..
..	..	300	..	..	..	..	36	61
·5000	..	..	61/·103″	..	..	..	..	..
·6000	..	..	91/·093″	..	..	..	..	..
..	..	400	..	..	..	..	..	61
·7500	..	..	91/·103″	..	..	..	..	..
..	..	500	..	..	91	..	..	..
..	1,000,000	..	..	61	..	..	..	..
..	..	625	..	..	..	..	..	..
1·0000	..	..	127/·103″	..	..	..	..	..
..	1,500,000	..	..	91	..	..	..	..
..	..	800	..	..	127	..	..	..
..	..	1,000	..	..	..	61	60	..
..	2,000,000	..	..	127	..	..	..	..

It will be seen from this Table that British stranding practice is more generous in the provision of flexibility in ordinary stranded conductors than foreign practice, just as it is in the matter of the limit of size of solid conductors mentioned above.

It may also be noted that German standards differentiate between the degree of flexibility required in paper and rubber insulated cables, as indicated by the number of wires specified to be used in attaining a given sectional area of conductor, whereas British and American standards make no such distinction.

According to the author's observation, German cable manufacturers do not actually follow the V.D.E. standard in the case of the largest sizes of stranded conductors, presumably because the large size of the individual wires (approaching a quarter of an inch in diameter) would render this impracticable.

The differences between the minimum number of wires specified by the V.D.E. for given sectional areas, according to whether a test wire is to be embodied in the conductor or not, is due to the fact that the test wire (1 sq. mm. sectional area), with its insulation, has—according to Continental practice—to be accommodated in the space of one strand.

With regard to the last column in the Table it may be mentioned that a footnote to the Table 904 in the American Standardisation Rules, from which these figures are abstracted, says :—

" Conductors of 4/0 American Wire Gauge and smaller are often made solid, and this table of stranding should not be interpreted as excluding this practice."

Stranded conductors are usually made by uniformly stranding successive layers of wire in opposite directions. From geometrical considerations, in a stranded conductor made up of wires of a given diameter, the number of wires in each succeeding layer will increase in arithmetical progression, the common difference being 6. Thus 6 wires round one centre wire are followed by 12, 18, 24, 30, 36, 42, and so on, to form 19, 37, 61, 91, 127, and 169 strand conductors. These are known as " regular " stranded conductors.

This construction represents the form most generally specified and used.

For certain purposes, such as the attainment of a particular effective area with a specified number of wires, or avoiding the use of a straight centre wire (desirable in some cases where strands have to be subsequently " shaped " or where excessive tensile stresses may be entailed by conditions of use), stranded conductors may be based on a centre of three or four wires stranded together. These, like the more usual form with single-wire centre mentioned above, are " regular " stranded conductors, the number of wires in each successive layer increasing in arithmetical progression, with a common difference of 6 wires.

In the former case the three-strand centre is followed by 9, 15, 21, 27, 33, and 39 wires to form 12, 27, 48, 75, 108, and 147 strand conductors, and in the latter the four-strand centre is followed by 10, 16, 22, 28, 34, and 40 wires to form 14, 30, 52, 80, 114, and 154 strand conductors.

Although the formation of stranded conductors on a three- or four-wire basis presents no appreciable difficulty in manufacture, there is no good reason—apart from the cases instanced above—why they should be used, and it may here be

remarked that there is a strong tendency at the present time to simplify the whole matter by standardising a limited number of sectional areas of stranded conductor gauges of wire and the simpler form of single wire centre strand to cover all general requirements,* this being clearly in the interests of both manufacturer and user, from the economic point of view.

The remarks on p. 140, Mechanical Principles of Design, regarding various kinds of flexible conductors, may be amplified from the constructional point of view as follows :—

Very fine wires (·0124″ and smaller), such as are used in electric lighting and other flexibles, are not amenable to stranding in the accurate mechanical sense of the term, on account of their comparative fragility, and are therefore assembled by " bunching," which consists of simply twisting them all up together at one operation while being paid off from their separate bobbins towards a converging point constituted by a die, as distinct from the layer by layer assembly in reverse directions employed in stranding.

In the case of large conductors in which an appreciable degree of flexibility in the sense of pliability, previously referred to (under Mechanical Principles of Design) as type (*b*), is required, and in which wires of the order of fineness above mentioned have therefore to be employed, the difficulty of mechanical weakness of the individual wires is overcome, and at the same time the mechanical requirements of the case are met, by dividing the total number of wires up into a convenient number of multiples, " bunching " each multiple, and stranding the " bunches " in " regular " formation, and in opposite direction to the lay of the " bunches." In such cases, especially when the conductor is uninsulated or only lightly covered—as in dynamo flexibles, or heavy flexible connecting cables of the non-portable type—it is often advantageous to reserve a suitable number of the wires for overall application, after stranding the bunches, in the form of a braid. This tends to prevent distortion, which may occur, for example, by flattening out the soft mass of wires on the barrel of a drum during manufacture, and generally exercises a controlling effect on the relative movement of the wires, thus militating against internal local kinking and subsequent breakage.

The flexibility of type (*c*) may be regarded as intermediate between pliability and an approach to springiness, attained by the simple expedient of using finer gauges of wire than are employed in ordinary standard " regular " stranded conductors. As stated in the preceding section, it is insufficient for either pliable or portable duty, although, as will be seen later (p. 148), the construction is standardised in America for flexibles smaller than No. 1, A.W.G., equivalent to ·0657 sq. in., and known in that country as " concentric " as distinguished from " rope-lay," *i.e.* multiple strand construction.

In American standards, however, smaller wires are specified than are usually employed in our so-called " Admiralty stranded " type, so that an approach is made to rather greater pliability ; but here again the author's observation is that for portable purposes practice does not generally follow the standard, which would appear to be chiefly laid down for machine connection and other non-portable work.

* See B.E.S.A. Report, No. 7, 1922.

TABLE IX

A.I.E.E. Table 905—Stranding of Flexible Cables

Nearest A.W.G. size (see Note 1).	Circular mils (see Note 2).	Diam. of cable, mils.	No. of wires.	Size of each wire.		Construction (see Note 3).
				A.W.G.	Diam., mils.	
..	2,039,000	1885	703	15·5	53·9	37×19
..	1,816,000	1779	,,	16·0	50·8	,,
..	1,617,000	1679	,,	16·5	48·0	,,
..	1,440,000	1584	,,	17·0	45·3	,,
..	1,284,000	1496	,,	17·5	42·7	,,
..	1,103,000	1372	427	16·0	50·8	61×7
..	874,600	1222	,,	17·0	45·3	,,
..	693,600	1088	,,	18·0	40·3	,,
..	550,000	969	,,	19·0	35·9	,,
..	436,200	863	,,	20·0	32·0	,,
..	345,900	768	,,	21·0	28·5	,,
..	274,300	684	,,	22·0	25·3	,,
..	264,600	671	259	20·0	32·0	37×7
0000	209,800	598	,,	21·0	28·5	,,
000	171,300	538	133	19·0	35·9	19×7
00	135,900	479	,,	20·0	32·0	,,
0	107,700	427	,,	21·0	28·5	,,
1	82,780	332	91	20·5	30·2	Concentric
2	65,650	295	,,	21·5	26·9	,,
3	52,060	263	,,	22·5	23·9	,,
4	39,190	228	61	22·0	25·3	,,
5	31,080	203	,,	23·0	22·6	,,
6	24,650	181	,,	24·0	20·1	,,
8	17,410	152	,,	25·5	16·9	,,
10	10,560	118	37	25·5	16·9	,,
12	6,640	94	,,	27·5	13·4	,,
14	4,176	74	,,	29·5	10·6	,,
Smaller	..	..	To equal required size	30·0	..	Bunched

Note 1. The A.W.G. cross-sectional areas, except for 61 strands, are approximated within 2 per cent. In the case of 61-strand cables the approximation is 6 per cent.

Note 2. Circular mils are based on theoretical diameters of A.W.G. sizes, which vary above or below values given in table by less than 0·1 mil.

Note 3. "61×7" in the rating of a rope-lay cable signifies 61 strands of 7 wires each.

Coming to the case of multiple stranded flexible conductors, previously referred to as type (*d*), in which flexibility is required to be combined with non-kinking properties, it will be clear that larger sizes of wire may with advantage be used than in

TABLE X

B.E.S.A. Table 4.—Conductors for Flexible Cables

(STANDARD ANNEALED COPPER)

1	2	3	4	5	6	7	8
	Diameter of each wire as at head of column.						
Nominal Area.	Number and diameter of wires comprising conductor.				Resistance per 1000 yards at 60° F.		
	Diameter 0·010 inch.	Diameter 0·012 inch.	Diameter 0·018 inch.	Diameter 0·029 inch.	Standard.	Maximum allowable for plain wires.	Maximum allowable for tinned wires.
Sq. in.					Ohms.	Ohms.	Ohms.
0·01	140/·010				2·29	2·34	2·39
0·0145	195/·010		60/·018*		1·64	1·68	1·71
0·0225	296/·010		91/·018*		1·08	1·11	1·13
0·03		266/·012	117/·018*		0·847	0·864	0·881
0·04		368/·012	163/·018*		0·606	0·618	0·631
0·06		557/·012	248/·018*		0·400	0·408	0·416
0·075		705/·012	313/·018	121/·029*	0·316	0·323	0·329
0·1			416/·018	160/·029*	0·238	0·243	0·247
0·12			482/·018	186/·029*	0·206	0·210	0·214
0·15			610/·018	235/·029*	0·163	0·166	0·169
0·2			810/·018	312/·029*	0·122	0·125	0·127
0·25			1017/·018	392/·029*	0·0974	0·0993	0·101
0·3				481/·029	0·0794	0·0810	0·0826
0·4				646/·029	0·0591	0·0603	0·0614
0·5				792/·029	0·0482	0·0491	0·0501

* For trailing cables and similar purposes.

The areas of the conductors in the above Table are given in nominal figures, an addition having been made to the number of wires to give resistances as nearly as possible corresponding to those for the same areas in B.E.S.A. Table 2.

the pliable types of conductor. This, together with the tendency—to which reference has been made—to limit the number of standard gauges of wire, has led to the employment of only four gauges of comparatively coarse wires in British Standard Flexible Cables (*vide* Table 4 of the B.E.S.A., No. 7, 1922, Report), viz., ·010 in., ·012 in., ·018 in., and ·029 in. (See preceding page.)

As previously noted, however, multiple strand formation of these flexible cables is not indicated, nor is there any recognised practice in the matter in this country.

The importance of the subject has always been better appreciated in America, and the standards of the A.I.E.E. have for many years included a specification of the formation of flexible conductors on the lines of the Table on p. 148 extracted therefrom.

It will be observed that there is a marked difference between the fundamental ideas of the British and the American standardising authorities, the former—as noted above—utilising only four sizes of wire, while the latter subordinates everything to the attainment of equivalents of standard sectional areas by " regular " stranding, even to the extent of using half-sizes of wire. The logical sequel—from the usage point of view—of stipulating the ratio of lay to pitch diameter, is not specifically referred to in either case.

The following Table, based on the sizes of wire specified in B.E.S.A. Table 4, and referring to the conductors marked " For trailing cables and similar purposes," shows suitable construction for cases where the conditions of service demand multiple stranding :—

TABLE XI

MULTIPLE STRANDED CONDUCTORS

Nominal area. Sq. in.	No. and diameter of wires, B.E.S.A., Table 4.	Approximate equivalent multiple strand.	No. of multiples in the layers.
·0145	60/·018″	12/·018″ plus 7/ 7/·018″	..
·0225	91/·018″	13/ 7/·018″	3 +10
·04	163/·018″	14/12/·018″	4 +10
·06	248/·018″	36/ 7/·018″	1 + 6 +12 +17
·075	121/·029″	18/ 7/·029″	1 + 6 +11
·1	160/·029″	24/ 7/·029″	3 + 8 +13
·12	186/·029″	27/ 7/·029″	3 + 9 +15
·15	235/·029″	34/ 7/·029″	1 + 6 +11 +16
·2	312/·029″	19/·029″ plus 66/ 7/·029″	8 +14 +20
·25	392/·029″	12/·029″ plus 91/ 7/·029″	1 + 6 +11 +16 +22

It will be noticed that adherence to the standard sizes of wire entails instances of " irregular " stranding in the assembly of the multiples ; for example, the two

intermediate layers in the case of the ·25 sq. in. conductor, in which the increment is five instead of six. These layers would have to be stranded up at a shorter lay in order to form a close sheath.

For most purposes any disadvantage in use which might accrue from irregular formation of the stranded multiples is negligible, but where the conditions of service entail very severe and frequent bending, regular stranding is to be preferred, because it affords the facility for maintaining the ratio of length of lay to pitch diameter at a constant value throughout the layers. This, of course, is the crux of the whole matter, as it reduces uneven relative movement of component parts to a minimum under bending conditions.

Such regularising in many cases often entails little more than the inconvenience of using a non-standard wire; for example, in the case of the ·25 sq. in. conductor above mentioned, the regular formation could be attained by the use of ·024 in. (23 S.W.G.) wire, in the form of 48/12/·024 in., the layer arrangement being 3 +9 +15 +21.

With regard to the estimation of diameters, weights, resistances, and effective areas of stranded conductors and lengths of wire comprising them, it may be noted that the virtual diameter of a 3-strand conductor (such as is commonly used in this country for electric light wiring purposes, or, as previously mentioned, for the centre of large stranded conductors) is 2·155 times—and of a 4-strand 2·414 times—the diameter of the individual wires of which it is composed. The overall diameters of stranded conductors having a single wire centre are simply 3 times the diameter of the wire for the 7-strand conductor, 5 times for the 19-strand conductor, and so on. The diameters of stranded conductors which have three- or four-wire centres can be readily calculated from the foregoing, and similarly the diameters of multiple-stranded conductors can be accurately computed.

The lay of a stranded conductor is, as mentioned on p. 133 (Nomenclature), usually referred to in manufacture in terms of "pitch diameter," which is of course equal to the overall diameter less the diameter of one wire.

The increase of length, weight, and resistance * due to the lay of a stranded conductor may be determined from the lay curve, Fig. 16, a deduction being made for the centre wire of a stranded conductor, which has, of course, no lay.

Multiplying constants, in terms of values for a straight single wire, are given in Table 12 for determining the weight, resistance, and effective area of ordinary stranded conductors on a basis of 2 per cent. variation †—as allowed for in the revised (1922) British Engineering Standards for insulated Electric Power and Light Cables—due to lay on all except the centre wires of the (7 and larger) stranded conductors.

Reverting to the earlier remarks (p. 147) regarding large flexible conductors of type (*b*), in which a proportion of the wires are braided over stranded bunches, it has to be borne in mind that the effective area of the wires used in the braiding is

* It is always assumed—and in actual practice it is the case—that the wires in a stranded conductor are practically insulated from one another.

† It will be seen from the lay curve, Fig. 16, that this corresponds to a lay of 15·63 times the pitch diameter.

considerably reduced as compared with the remainder by reason of the much shorter lay at which they are applied. (See lay curve, Fig. 16.) Also that in the main

TABLE XII

STRANDING CONSTANTS

Strand.	Weight.	Resistance.	Effective Area.
3	3·06	0·3400	2·94
7	7·12	0·1453	6·88
19	19·36	0·0536	18·64
37	37·72	0·0275	36·28
61	62·20	0·0167	59·80
91	92·80	0·0112	89·20
127	129·52	0·0080	124·48
169	172·36	0·005928	165·64

portion of the conductor, *i.e.* the stranded bunches (and similarly in the case of multiple stranded conductors) the increase of weight and resistance due to lay has two components, viz., one due to the lay of the multiples themselves, and the other to the stranding of the multiples together. If, when insulated, such conductors are used to form multicore cables, a third allowance has to be made for the lay of the cores.

As is well known, conductors offer a greater resistance to the passage of alternating than to continuous current, due to the fact that—if the conductor is regarded as a series of independent conducting tubes or layers—the innermost layers have a greater reactance than the outer, and the current density naturally varies in inverse ratio, so that instead of it being uniform across the whole section of the conductor, as in the case of continuous current, it is greater in the outer layers than in those nearer the centre of the conductor. This is the so-called " skin effect."

The ratio of this apparent resistance (Ra) to the true resistance (Rc), represented by the constant K, is dependent—for a material of given conductivity—on the diameter of the (circular) conductor and on the frequency. Values of K corresponding to a range of values of d^2f (where d is the diameter of the conductor in inches and f the frequency) are given for copper in various books of reference.

They are derived with more or less accuracy from the theoretical formula first enunciated by Maxwell * (and subsequently in modified form by Lord Kelvin †), of which Russell, in his work on Alternating Currents ‡ has developed a complete solution by means of the ber and bei functions.

It will be noted that values of K for any other non-magnetic metal may be determined, according to its relative conductivity, as a simple ratio of the values for copper, because the conductivity varies as d^2, as also does the value of K for a given frequency.

* J. Clerk Maxwell, *A Treatise on Electricity and Magnetism*, vol. ii., Art. 690.

† Presidential Address to I.E.E., 1889.

‡ A. Russell, *Alternating Currents*, vol. i., 2nd Edit., Chap. VII.

It follows that, contrary to a common impression, the larger diameter of conductor necessitated when a metal of lower conductivity is substituted for copper entails no greater loss due to skin effect. This is exemplified in the diagram (Fig. 21), in which values of K, calculated according to Russell (*l.c.*, *ante*), are plotted against sectional area of circular stranded conductors for copper and aluminium at 50 and 25 cycles respectively.

A cursory inspection of the curves shows that the value of K at a given frequency

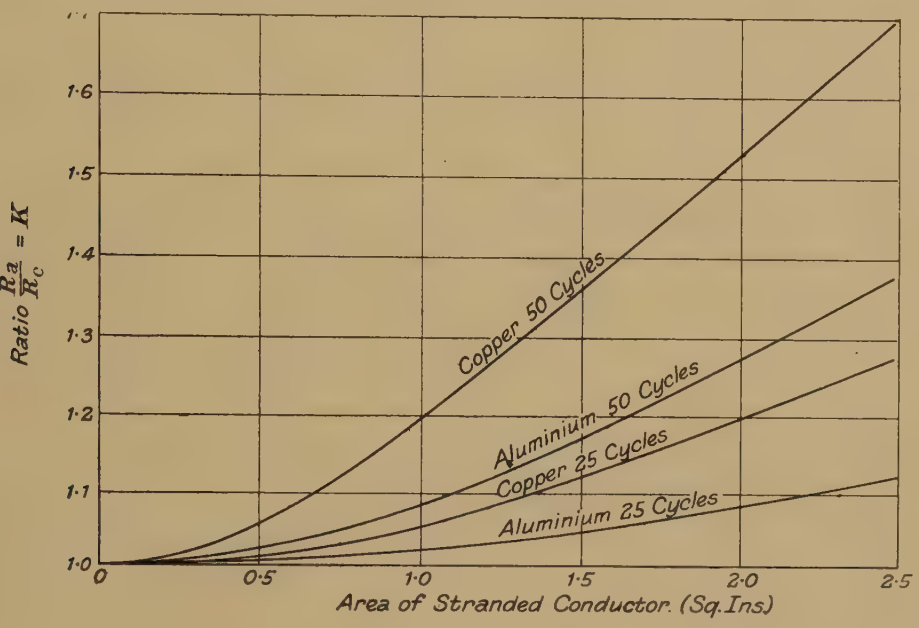

Fig. 21.

is the same for a given sectional area of copper as for an area of aluminium 64 per cent. greater; *i.e.*, for equal conductivity.

(Standard stranding has been assumed, and the sectional areas are calculated on the overall diameters of the stranded conductors.)

Another factor in the increased resistance of a stranded conductor to alternating current is said by some writers to be due to the solenoid effect of the spiral paths followed by the strands. Certain proposals have been made to reduce these eddy current effects generally by interposing light insulation between various parts of the stranded conductor.

In large single-phase (concentric) cables the " skin effect " was to some extent combated in the early days by stranding the inner conductor of concentric cables over a rope centre.

Present day high-tension, three-phase practice, at frequencies not usually exceeding 50∿, has generally tended to make the whole matter negligible, so far as transmission cables are concerned, electrical requirements relating to the three-

phase system, and limits of size of the cables—containing, as they usually do, three conductors—keeping the size of conductors below that at which the effects in question are appreciable.

Large single cables are, however, occasionally used in generating and substations between machines and switchboards, rendering it necessary to either employ the rope-centre construction above referred to, or to use conductors of such size as will compensate for the skin effect by keeping the current density low. As will be seen from Fig. 21, the effect in non-magnetic conductors is practically negligible in sizes below approximately ·4 square inch.

The more complicated case of magnetic materials (iron, steel, and composite conductors), entailing considerably higher values of K, does not come within the scope of this work.

SHAPED CONDUCTORS

There is a considerable proportion of waste space in multicore cables when circular conductors are employed, and consequently appreciable economy in material and reduction of diameter may be attained by shaping conductors.*

In the case, for example, of a 3-core paper-insulated cable, the sectional area of the waste space which has to be filled with " worming " or " padding " when the cores are circular, is equivalent to $1{\cdot}29\ d^2$, where d = diameter of one insulated core.

If each core in such a case could be made of true sector form with its sides at 120° to each other, the whole of this waste space would be eliminated. Further, the diameter over the laid-up sector cores would be reduced as compared with circular cores from the equivalent of $D = 2{\cdot}155d$ to $D = 1{\cdot}8d$ approximately.

For a combination of manufacturing reasons and electrical stress considerations, however, full advantage cannot be taken of this. As regards the former, it has already been pointed out (Mechanical Principles of Design, p. 142) that shaped conductor cores, of necessity, have a twist put into them in the laying-up process, and it will be readily appreciated that the more definitely a conductor is shaped, the more it will resist laying-up.

With regard to electrical stresses, too definite shaping produces not only sharp edges at the angles of the sector but also (regarding the conductor longitudinally) a serrated line along each edge.

It is common experience that in factory breakdown tests on shaped conductor cables, the ultimate failure almost invariably occurs at these regions of accentuated stress.

It therefore becomes necessary to slightly modify the theoretically desirable true sector shape to minimise these disadvantages, and the main object of design is to balance them against the advantages of economy of material and reduction of diameter and weight in the completed cable.

The net practical result is that relatively little economy is attainable by shaping very small sizes of conductor, unless they are small enough to be made of shaped

* Ferranti appears to have been the first to propose the shaping of conductors for various types of multicore cables (Patent No. 22923/92). The first practical exponents were the B.I. & H. Co.

strips, because the size of an individual strand is large in relation to the cross-section of the whole conductor.

To a certain extent this may also apply to conductors of medium size which are very heavily insulated, in which case the advantage of shaping tends to decrease, because the configuration of the conductor is less sharply followed by succeeding layers of paper as the dielectric thickness increases.

In view of these considerations, British practice has not favoured the use of shaped conductors for working pressures exceeding 11 K.V., although in America they have been used at all voltages up to and including 33 K.V. It is significant, however, that American specifications lay considerable stress on the symmetrical assembly of shaped cores, and specify definite tolerances or limits of dissymmetry.

For example, the N.E.L.A. (National Electric Light Association) Specification for Impregnated Paper-insulated, Lead-covered Underground Cable, Section 5 (*g*), reads : " In sector-conductor cables the axes of symmetry of the conductors shall not be turned more than 20 (twenty) degrees from the normal position."

The Brooklyn-Edison Co.'s specification in connection with 33 K.V. cables is still more exacting, as follows : " The axis of symmetry of no individual conductor shall form with a radius from the centre about which the conductors are assembled, and through the centre of the conductor, an angle greater than 10 degrees in a four-conductor cable, or greater than 15 degrees in a three-conductor cable. The axes of symmetry of two adjacent conductors shall form an angle of between 65 degrees and 115 degrees in a four-conductor cable, and between 95 degrees and 145 degrees in a three-conductor cable."

In L.T. paper insulated cables, twin cores are frequently made with D-shaped conductors, while in 3-core cables for three-wire C.C. distribution, and 4-core cables for three-phase distribution, the smaller neutral core is sometimes made circular and laid up with the main cores—made in sector form.

Obviously, considerable variations in shape can be made to suit special forms of cable, but from the above-mentioned considerations it will be clear that there are decided practical limitations in the matter.

There are two general methods of shaping commonly employed, *i.e.* (*a*) by rolling or hammering ordinary circular stranded conductors, and (*b*) by stranding to the required shape.

The former method (*a*) entails the greater tendency to produce serrated edges, and special attention to the design of rollers and anvil dies is necessary.

In the latter case (*b*), wires are stranded round a matrix, formed by an assembly of wires of different diameters or a suitably arranged number of wires of the same diameter. The angles are therefore less sharp, and electrical stresses thereat less accentuated. In either of these assemblies, however, the wires forming the matrix are run straight (*i.e.* unstranded) through the centre of the stranding machine, their correct relative positions being maintained by a die plate, and have to be kept uniformly taut until they are bound up by the surrounding wires stranded over them.

It is also necessary to bind the finished shaped conductor with a lapping of tape or paper strip at the end of the stranding machine before the conductor is bent round

the haul-off wheel, in order to prevent buckling or " dog-legging," due to uneven distribution of mechanical stresses in the conductor.

Within certain narrow limits of size it is preferable to use a solid shaped " rod " as the matrix of a shaped strand. While this facilitates the building up of the stranded conductor, and also allows it to more readily take the desired permanent set (previously referred to) when the insulated cores are laid up, the comparative stiffness of the centre strip limits the use of the method to small sizes.

From first considerations it will be clear that a limit is placed on the radius to which shaped conductors should be bent.

In the former (rolling or hammering ordinary circular stranded conductors), flexibility is reduced because the spiral formation on which flexibility depends is interrupted at each angle ; and in the latter (stranding to shape) because the centre wires forming the matrix are not spiralled.

Each method, therefore, has advantages and disadvantages from the electrical and mechanical standpoints, and each is subject to the overall factors of process design and workmanship.

It may be added that the two general methods are in some cases combined by submitting the conductor shaped by stranding to a limited amount of rolling or hammering treatment, and a judicious combination of both probably represents the best average practice.

The electrostatic capacity of a shaped conductor cable is naturally greater than that of a round conductor cable of equal effective area, the difference usually being of the order of 8 to 10 per cent.

For reasons connected with manufacturing operations and the physical properties of insulating materials, the use of shaped conductors is practically limited to the paper-insulated or varnished cambric types of cable—the latter, however, up to the present, to a limited extent.

It is, of course, not impossible to insulate shaped conductors with the non-fibrous insulating materials, but the difficulties regarding retention of shape of the insulated cores during manufacturing operations preceding the laying-up process, and the mechanical considerations referred to earlier in this chapter (Mechanical Principles), usually preclude the use of shaped conductors in conjunction with these types of dielectric.

Segmental strips are sometimes used in place of D-shaped stranded conductors for small twin paper insulated, lead covered house wires.

FORMS AND DISPOSITION OF CONDUCTORS

The fundamental desideratum in this connection is, of course, the attainment of maximum carrying capacity for a given weight of conductor material.

In its broadest sense this primarily depends on the system of distribution, and secondarily—from the point of view of cable design—on the forms and disposition of conductors in the cables.

Although we are not here concerned with the design of distribution systems, it may with advantage be pointed out to the cable user that comparisons which are sometimes given regarding the economical advantages of different systems are liable to be misleading unless all factors and assumptions are known. For example, the following table shows the difference between assuming equal voltages between "outer" conductors (case A) and equal voltages between outer and neutral, that is, on consumer's circuits (case B).

In each case an equal amount of power to be carried and an equal percentage drop in voltage is assumed. For simplicity also, the power factor in the A.C. circuits is taken as unity, and the neutral conductors are taken as half the sectional area of the main conductors, except, of course, in the case of the two-phase three-wire system.

System of Distribution.	Relative weights of conductor material.	
	Case A.	Case B.
C.C. (or single-phase A.C., two-wire)	100	100
C.C. ,, ,, ,, three-wire)	125	31·2
A.C. two-phase, three-wire . .	170	85
A.C. ,, four-wire . .	100	100
A.C. three-phase, three-wire . .	75	75
A.C. ,, four-wire . .	87·5	29·2

The basis of case A bears largely on the case of feeders, while that of case B represents distribution conditions, and it is therefore clear that in the broad primary sense above referred to, economy with regard to conductor material depends on the permissible distribution voltage (which in turn is determined by the character of consuming apparatus) and not by cable-making considerations.

From the aspect of cable design, the relation of the above-mentioned fundamental desideratum to forms and disposition of conductors resolves itself into the twofold matter of (*a*) minimum loss and (*b*) maximum heat dissipation.

With regard to (*a*), minimum inductive losses are ensured in A.C. cables by symmetrical arrangement of their conductors, while (*b*) is best attained by so disposing conductors in either C.C. or A.C. cables that the heating of one conductor affects another to a minimum extent. For example, a twin has an advantage over a concentric cable and a 3-core over a triple concentric in this respect.

In this connection it should not be overlooked that maximum carrying capacity is dependent not only on the make-up of a cable and the form and disposition of its conductors, but also, to a greater degree than is generally appreciated, on the nature of its dielectric and protective coverings and the method of laying or installation.

Generally, the forms and relative dispositions of conductors in cables for use on different systems are as indicated below, and diagrammatically represented in Fig. 22.

Fig. 22.

(*A*) Continuous Current.—Single, twin, concentric, triple concentric.
(*B*) Single Phase Alternating Current.—Twin, concentric.
(*C*) Two ,, ,, ,, Twin-concentric or one concentric per phase.
(*D*) Three Phase Alternating Current.—3-core, or 4-core.

In (*A*) the outer conductor of the triple concentric, and in (*D*) the fourth core of the 4-core cable are neutral or balancing conductors. General practice is to make these conductors half the sectional area of a main conductor, this usually being sufficient for the conditions obtaining on fairly well-balanced systems. There is of late, however, a general trend of opinion among mains engineers in favour of making all the conductors in these types of cable uniform in size.

The size of the neutral (outer) conductor of the twin-concentric cable (*C*) is approximately fixed by the fact that it has to carry $\sqrt{2}$ times the phase current, and its effective area therefore has to be $\sqrt{2}=1{\cdot}414$ times that of a phase conductor.

The use of concentric and triple-concentric cables for ordinary mains—except in single-phase A.C. work—is diminishing considerably in favour of the twin and 3-core types respectively.

Apart from smaller diameter as compared with twin and 3-core construction, the concentric form has little to recommend it, although the dimensional advantage is of importance in places such as sub-stations and distributing chambers where large numbers of low-tension distributors have to be accommodated, and the smaller compass required by concentric terminal boxes is of moment.

From both the manufacturing and usage points of view—the latter including jointing considerations as well as those of current-carrying capacity already referred to—they compare unfavourably with the twin and 3-core types. With regard to construction, it is clearly desirable from both aspects that the concentrically arranged conductors should form a close sheath over the underlying insulation, and a moment's consideration will show that this does not readily fall in with conductor area requirements.

For example, in the case of a cable having an inner conductor of small sectional

area, a close sheath of the smallest practicable size of wire will have a greater sectional area than the inner conductor; whereas, on the other hand, in the case of

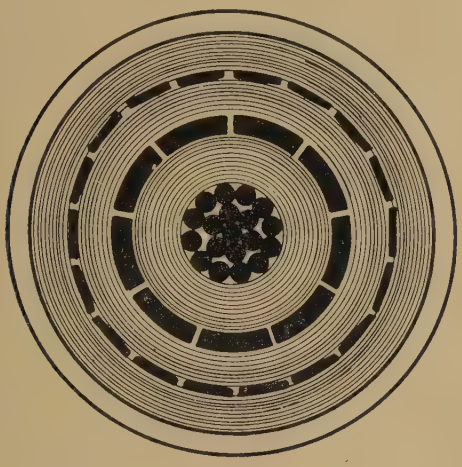

Fig. 23.

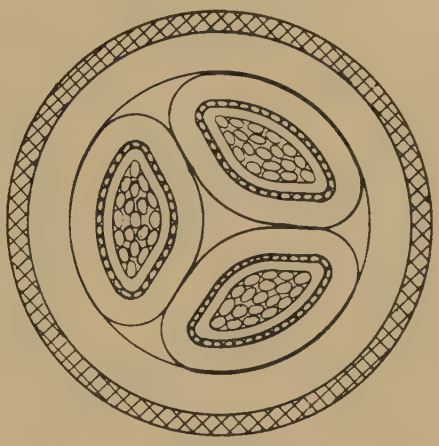

Fig. 24.

a cable having a large inner conductor, the outer—if made up of wire—may require to be applied in two or more layers. This would entail interstitial spaces in the

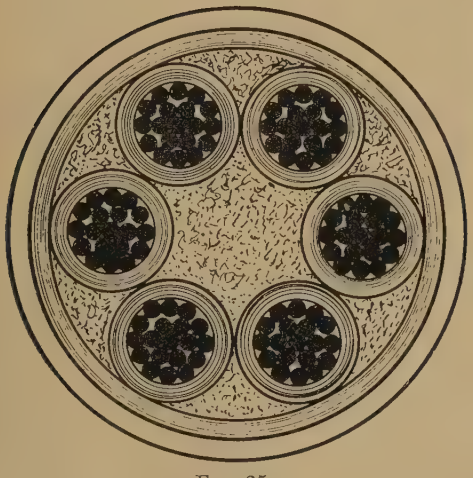

Fig. 25.

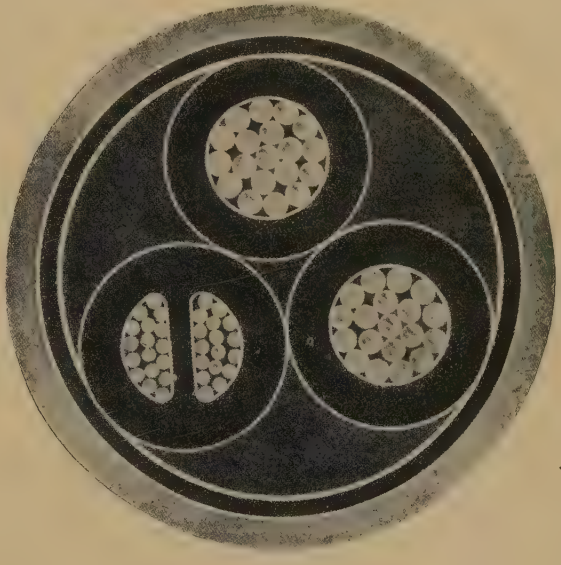

Fig. 26.

annulus occupied by the outer, which would not only inflate the diameter of the cable, but would constitute a great disadvantage in the event of ingress of water, by allowing it to pass readily along the cable. In large sizes, therefore, the concentric

conductors are made of strips, sometimes simply rectangular in section (when the thickness in relation to width is small), but more usually drawn to a segmental shape.

Fig. 23 shows a section through a triple-concentric cable in which the intermediate conductor is made of strips of the latter type, and the outer of the simple rectangular form.

A common variation of the three-phase H.T. construction consists in accurately dividing (as regards impedance) the conductors into halves and laying them up, after insulating them, in a manner suitable for the split core (Merz-Hunter) system of feeder protection.

Formerly the halves of each conductor were combined in twin or concentric form—usually the latter—lightly insulated between the halves, and the main core insulation applied overall, and thereafter treated as one core of a 3-core cable, as shown in Fig. 24.

More recent practice is to lay up six fully insulated cores around a centre rope of impregnated paper, as in Fig. 25—diametrically opposite cores being coupled in one phase.

A still later proposal is to split one phase only, one conductor of a 3-core cable being made up as a *D*-shaped twin, as shown in Fig. 26.

SPECIAL ASSEMBLIES

In addition to the more common arrangements or groupings of the main insulated conductors referred to in the preceding section, it is often necessary or desirable to employ a variety of auxiliary conductors in conjunction with them for such purposes as supplementing the conductivity of the metallic sheathing (earth shields), measuring the voltage drop on the line, or testing the location of faults (pilot or test wires); the actuation of protective gear; the distribution of potential in the dielectric; or for the purpose of fulfilling "test sheath" functions. In some of these cases it is essential, and in others often convenient, to embody the said conductors in the main cables.

Earth shields are comparatively seldom used nowadays, because the conditions under which they were originally specified by the Board of Trade have passed away, viz., where small isolated E.H.T. feeders having a radial thickness of lead sheath less than ·01 in. were used. Their function was to assist in preventing the cable surroundings becoming charged to a dangerous potential in the event of a fault to earth; and they were specified to consist of either a copper tape, not less than ·016 in. in thickness, applied immediately under and in contact with the lead sheath, or a sheath of galvanised steel wires, not less than ·01 in. in diameter, laid directly upon the lead sheath.

It may be noted in passing, that the matter of lay was apparently overlooked in specifying the copper tape alternative; bearing in mind that, of necessity, the tape must be applied at a short lay, a glance at the lay curve (Fig. 16) will show

that its resistance would be comparatively high, thus defeating the object with which it was specified. Those who appreciated this point interpreted the rule as meaning a number of strips applied at a long lay, instead of a tape which necessarily had to be wound on at a short lay, and specified or manufactured accordingly. The alternative of an external sheath of steel wires was, of course, much more effective for the purpose in view.

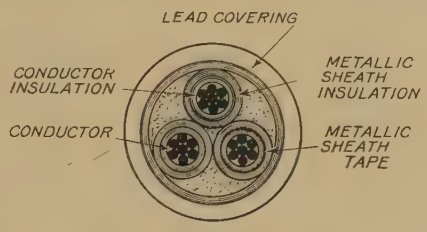

FIG. 27.

With regard to pilot and test wires, standard Continental practice favours their embodiment in the outer layer of main-stranded conductors, in place of one of the strands, as indicated in Table VIII, p. 145, from which it will be seen that in what would ordinarily be a 37-strand conductor, the total sectional area is divided up into 36 wires, and the thirty-seventh space utilised for an insulated pilot wire.

Although British cable-makers have, of course, to follow this method of construction in cables for use in certain foreign countries, it is hardly ever used in ordinary British practice, which either takes the line of a separate pilot cable, or—in the case of twin or multicore cables—laying up the pilot, test, and (sometimes) telephone wires in the interstitial spaces between the insulated cores. At high pressures, the latter assembly is not economically feasible, because of the increased amount of insulation which it is necessary to apply to the subsidiary conductors, as, obviously, they have to be insulated for the line pressure; the separate cable principle has therefore to be resorted to.

Such separate cables are, however, at some disadvantage by reason of their comparative fragility, and their failure on this account has been a serious drawback in the past to certain protective systems in connection with which they have been employed. Modern conditions have, however, tended to bring about an improvement in this respect, not only on account of better manufacturing facilities and an appreciation of the necessity of substantial thicknesses of dielectric, but because for operating reasons these auxiliary conductors for protective systems are almost invariably made in concentric form (according to the Beard-Hunter system), which makes a larger and more substantial cable to withstand the exigencies of armouring, laying, etc.

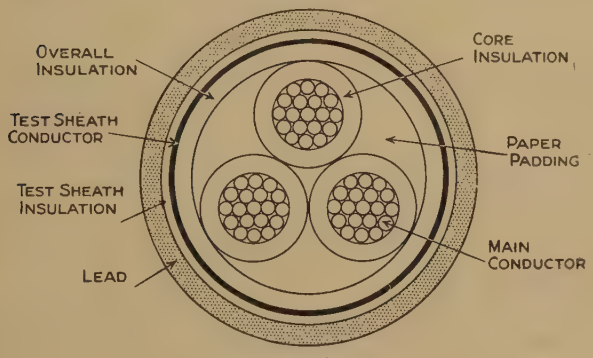

FIG. 28.

Fig. 27 shows a typical assembly of a Beard-Hunter pilot cable.

In some cases it is an essential feature of protective systems that the auxiliary

conductors required for their operation should occupy certain positions in the cable relative to the main conductors or to the metallic sheath. An example of the former is the Pfannkuch system, in connection with which the main conductors of the cable are surrounded by a layer of small separately insulated wires; each series of three of these wires having—in operation—one wire at normal voltage minus 5 per cent., one at normal voltage, and the third at normal voltage plus 5 per cent.

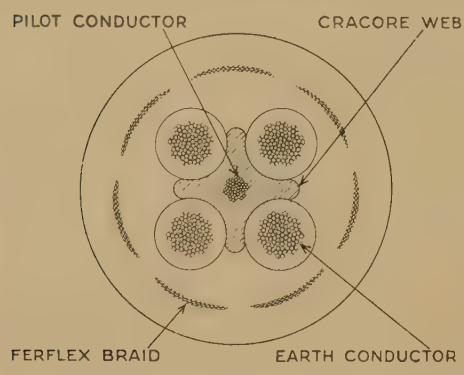

Fig. 29.

An example of a case in which relation of position to the lead covering is essential is the author's Test Sheath system, in which the auxiliary conductor consists of a copper tape or a series of metal strips or wires surrounding the whole of the main dielectric and separated from the metallic sheath of the cable by a thin hygroscopic dielectric. This form is illustrated in Fig. 28, and is further referred to under Maintenance, Vol. II.

In some instances, such as the Williams-Rowley system, a combination of the two essentials is involved, *i.e.* a pilot wire in the centre of the cable, and also a sheath of wires surrounding the whole of the insulated cores. This is illustrated in Fig. 29.

Generally, it will be noted that in these cases of inclusion in the main cable, from the nature of the functions of the auxiliary conductors (apart from considerations of manufacture) their embodiment in the cable falls into the usual symmetrical assembly, which is a root principle in cable construction.

CHAPTER VIII

DIELECTRICS

COMPOSITION DESIGN

In a Paper * which Mr Mervyn O'Gorman read before the Institution of Electrical Engineers in 1901, he indicated the following desiderata for a perfect cable dielectric :—" waterproof for 100 years, flexible and extensible, so volt resisting that the thinnest film suffices, with a specific capacity almost as low as that of air, yet adjustable to a high value ; sufficiently firm not to decentralise, yet fluid enough when heated by an arc to close in and seal up a fault." He further added that it should be made for five pence per lb. applied to the cable. These desiderata would seem sufficiently idealistic, but the conditions of to-day would necessitate the addition of others, such as negligibly low power factor, great heat conductivity, non-flammability, resistance to all kinds of deteriorating influences (chemical, electrolytic, hydrolytic, etc.), and the retention of all these properties under all conditions of working temperature.

Undoubtedly Mr O'Gorman had in mind intensive scientific research as the means of approaching his ideals, but apart from the lamentable lack of scientific enterprise in such directions, the general advance in the uses of cables under all kinds of new conditions has continually shifted the basis on which any such research could be made. Causes of trouble and deterioration under such expanded conditions of use have made prior claims on the resources of the industry so far as research is concerned, and apart from the commercial aspect of the matter, the state of our scientific knowledge at the present day is not such as to render it either hopeful, likely, or even practically possible that any natural, synthetic, or manufactured substance can even remotely approach the desired combination of physical, chemical, and electrical requirements.

Hence we are still forced to use a number of dielectric materials having different properties, choosing them according to the purposes and the conditions for and under which they are to be employed ; grading them as regards composition, proportioning them as regards dimensions, and disposing them in relation to the conductors according to the electrical requirements ; protecting and reinforcing them in various ways and with different materials according to their physical and chemical limitations ; and last, but by no means least, doing all these things with due regard to cost.

This latter point deserves some passing consideration because, apart from the fact that competition, standardisation (and less tangible factors such as conservatism) tend to prohibit even the practical trial of a new dielectric material unless the cost is low enough to constitute a strong commercial inducement, there is a broad economic aspect which should not be overlooked. Supposing that a dielectric material could be produced which would even remotely approach the above-

* *I.E.E. Journal*, vol. 30, p. 609.

mentioned ideals, it would obviously be of such great technical value—not only in cable manufacture but in a large number of other industries—that its price would naturally and automatically bear some relation to the value of materials which it displaced, at least in the initial stages of its production. At a later stage the law of supply and demand, together with the factor of esteem in which the material was held by manufacturers and users, would effect a general stabilising of price.

In view of the more or less artificial economic position which such a superlatively excellent material would occupy, it is extremely problematical as to whether the most (commercially) efficient course is the present one of improving existing types of dielectrics, or the alternative of striving after an ideal substance which would constitute a panacea for all the troubles and shortcomings—whether well known or only partially appreciated or imperfectly investigated—which appertain to dielectrics.

Whatever the future may hold in the latter direction, however, it is quite certain that the present-day situation renders it necessary to pursue the former course, although the foregoing consideration of ideals may not be without use in adding depth of focus to the broad view of " things as they are " in connection with dielectric design.

Pursuing this view, and recalling the general aspect referred to in Chap. I, p. 25, from which it was seen that each type of dielectric at present in use has, more or less, a field of its own, and that the combination of technical and commercial circumstances have roughly circumscribed their spheres of utility, it is clear that while there is considerable scope for improvement of each type there are certain obvious limitations to the extent to which the mechanical, physical, chemical, and electrical advantages of one may be shared by another.

For example, it would be absurd to expect the mechanical and physical properties of rubber to be shared by paper.

In all types, however, the fundamental desiderata relate to permanent electrical properties such as maximum specific insulation resistance and dielectric strength and minimum specific inductive capacity and power factor, although the relative importance of these properties will vary according to the electrical conditions, *e.g.*, the voltage for which the dielectrics are designed.

Given these electrical desiderata, it becomes clear that an insight into general mechanical, physical, and chemical considerations is desirable in order that the components of the dielectric materials may be intelligently selected and the composition design rendered efficient.

Taking these considerations *seriatim*, the mechanical requirements—which are by far the simplest—demand firstly, amenability to the production and application of dielectric materials by practical workshop methods ; and secondly, in the finished goods, either tensile strength (in the case, for example, of fibrous dielectric materials) or elasticity, resilience, and toughness in the case of rubber or vulcanised bitumen.

The relation between mechanical properties and physical structure is obvious.

Physical considerations, in the case of impregnating materials for fibrous dielectrics, are fairly simple, and relate chiefly to such points as the solubility of the components of the impregnating compound in one another, viscosity of the compound over the range of temperature represented by manufacturing and working conditions, and avoidance of dialysis effects in impregnating, whereby crystallisable components are separable from non-crystallisable ones, and so on.

In non-fibrous dielectrics such as vulcanised rubber and vulcanised bitumen, the physical considerations bear not only on admixtures of colloidal, crystalline, and amorphous substances but are complicated by the chemical combinations which occur in vulcanisation. Moreover, the physical structure of the resultant body is undoubtedly affected by the " mechanism " of such chemical combination, with the further complication that variation in such structure may possibly be mechanically and physically beneficial, but on the other hand electrically deleterious, *e.g.*, by permitting absorption of moisture, or may produce the converse effects.

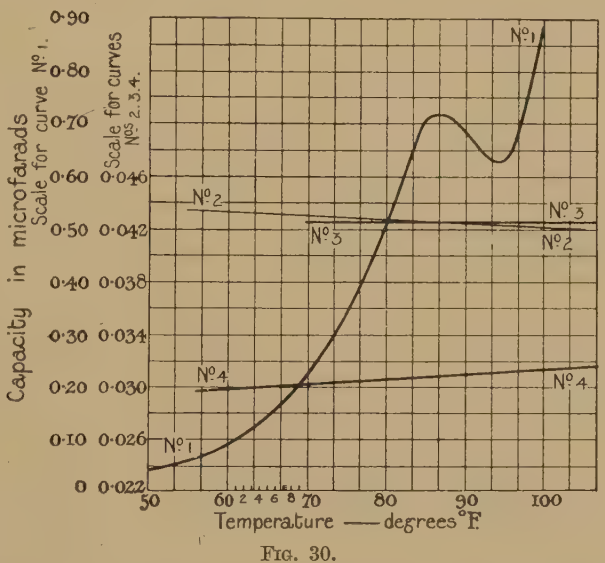

Fig. 30.

Chemical considerations in all types of dielectrics demand that the ultimate combination of components —whether such combination be physical or chemical—shall be stable at all temperatures likely to be encountered in use, and that they shall have no deleterious effects on conductors or other adjacent components of the cable. Further, that they should contain no substances electrolysable or ionisable at potentials appreciably lower than those at which other components may suffer decomposition of this general character. Resistance to various inimical influences of more or less chemical character, such as atmospheric influences, gases, light, enzyme action, hydrolysis, etc., and in the case of hygroscopic dielectrics to absorption of water, may be obtained by special admixtures or by resistant coverings ; these will be referred to later.

Even a cursory survey of the foregoing considerations makes it apparent that they are more or less interrelated and interdependent.

Typical instances of this interdependence are referred to in the author's Paper on " Cables " ; * and one or two, representative of and intimately connected with the composition design of dielectrics may be usefully cited at this juncture.

Fig. 30, reproduced from the above-mentioned Paper, relates to compounds

* *I.E.E. Journal*, vol. 53, p. 64.

used for the impregnation of paper dielectrics, and illustrates the variation of capacity with temperature. Over the range of temperature referred to in the diagram, compounds 2 and 4 are shown to have slight negative and positive temperature coefficients respectively. Compound No. 3 has practically no temperature coefficient, while compound No. 1 not only possesses a high specific value and a large temperature coefficient, but also shows peculiar variations over a certain range of temperature (85° to 98° F.).

The connection between these results and physical properties of the various compounds may be gathered from the following notes regarding composition :—

Compound No. 1 is composed of mineral oils, waxes, and resin.
Compound No. 2 is composed of resin oil, waxes, resin, and a small proportion of mineral oil.
Compound No. 3 is composed of resin and resil oil.
Compound No. 4 is composed of a crystalline solid (mineral) wax.

The great difference between the results obtained from the somewhat similar compounds 1 and 2 is due to imperfect adjustment of the former for electrical properties, resulting not only in higher specific inductive capacity but also in a very different order of temperature coefficient and the peculiar variations above noted, the former being due to composition *per se*, and the latter to rearrangement of solution of some components in others. On the other hand, compound No. 2 had been carefully designed for electrical properties and adjusted for critical points and other possible variations. Compound No. 3 was a true solution at all temperatures over the range in question. Compound No. 4 had a definite chemical composition and a melting-point (132° F.) well above the temperature range indicated in the diagram.

Since the publication of the author's results, to which Fig. 30 refers, Clark and Shanklin have found (*Proc. A.I.E.E.*, vol. xxxvi., p. 465, June 1917) that in the case of a certain compound which they refer to as a " mineral hydro-carbon base cable compound," and also in the case of a heavy mineral insulating oil, values of relative permittivity (*i.e.* relative specific inductive capacity) varied in a manner closely corresponding to the variation of specific gravity values of the materials over a range of temperature.

Another instance of the interdependence of chemical, physical, and electrical properties, referred to in the author's Paper (*l.c.*, *ante*), related to vulcanised rubber, the author pointing out that " if we modify rubbers specially designed for insulating purposes by introducing into them ingredients which are commonly and satisfactorily used in mechanical rubber goods for the express purpose of obtaining maximum strength and elasticity, we may find that even so small an addition as 0·5 per cent. of certain ingredients may result in a reduction of something like 50 per cent. in the insulation resistance. This, in itself, might be comparatively harmless, but another extraordinary result from the electrical point of view is that in spite of the physical improvement the molecular structure is so modified by such additions that the insulation resistance falls very appreciably after the cable has

been immersed in water for a few hours owing to the absorption of minute quantities of water, whereas insulating rubbers show no such alteration."

Again, in the case of vulcanised bitumen, the author has shown that the addition of certain percentages of a colloidal substance which had little appreciable effect on electrical or mechanical properties of the material, showed a very marked chemical advantage in imparting resistance to certain hydrolytic action.

COMPOSITION DESIGN OF PAPER DIELECTRICS

Sufficient has probably been said in Chap. IV to indicate that the most desirable class of paper for use in the composition of an impregnated paper dielectric is one made from fibres of the pectocellulose group. Further reference, with experimental proof regarding the durability under conditions bearing on those which obtain in practical use, will be made to the point in Chap. IX Dielectrics—Properties and Limitations. Certain comparisons relating to electrical properties will also be referred to.

It need only therefore be noted in passing, that all comparisons made by the author, whether bearing on electrical or chemical properties, between cable papers of the pecto- and ligno-cellulose types, give results which are in favour of the former. So far as the author is aware, the only argument which has been advanced in favour of the latter type is that wood-pulp papers are purer than manilla, in the sense of being freer from extraneous matter. While in the past this has to a great extent been true, it is not of necessity so in recent years, the demand for cable papers having become of sufficient importance for paper-makers to produce paper from new—as distinct from waste—fibres, thereby avoiding contaminations such as the oil in old ropes, which led to carbon spots, etc., in the finished product. The exact degree of importance attaching to the differences between the two classes of paper can only be demonstrated by results obtained from operating experience, but it is obvious that with advancing values of dielectric stress, the chemical risks—whatever they may amount to—will be appreciably enhanced, and in the absence of electrical advantages it would appear that the chief object in using the wood-pulp papers is economy in first cost.

The relative parts played (electrically) by the two components in an impregnated paper dielectric, viz., paper and compound, cannot be determined with any great degree of accuracy on account of the difficulty of testing the former in an air-free condition. A cursory glance at their respective electrical properties, so far as they can be determined or deduced, is, however, not without interest.

Considering first the paper, and assuming complete expulsion of its natural moisture, it will be apparent that its cellular structure entails an appreciable air content, and therefore that its dielectric strength will be low, but that it will have high insulation resistance and low capacity.*

Regarding next the impregnating compound, as might be expected from its more homogeneous character, its dielectric strength is considerably higher than that of the paper, but its other electrical properties are less favourable.

* See Table XIII, p. 186.

Coming to the combination represented by the impregnated paper, in which the air in the paper is replaced by the impregnating medium, it is found in practice that its dielectric strength is of the same order as—or slightly greater than that of —the compound; the inference, therefore, being that the dielectric strength of the air-free cellulose is at least as high as that of the compound. The actual value of the dielectric strength of the impregnated paper is about three times that of the dry but air-containing paper. The other electrical properties of the combination are of the same order as those of the compound, the specific inductive capacity being about twice that of the dry paper, while its specific insulation resistance is considerably lower.

It should be understood that, in the foregoing remarks, paper of the class generally employed in impregnated paper cables is referred to. This is rather important, because from a broad survey of the results of many tests carried out by the author over a number of years, it would appear that structure or texture has even more influence on actual values than the composition of the fibrous material.

For example, in a given paper, a difference in density due to a greater degree of calendering may produce appreciably greater dielectric strength, as determinable by puncture tests.

Again, a cotton paper, which by reason of its pure cellulose composition might be expected to show superlatively good dielectric strength, fails to do so if it is too finely beaten.*

(Incidentally this illustrates the futility of comparing the properties of papers on the basis of composition, without regard to the general order of their structure or texture.)

The following figures represent average results obtained by the author in the course of a wide series of experiments on puncture voltages of various classes of paper, selected as bearing on the foregoing. The papers were impregnated under constant conditions, and tested in double sheets averaging 14 mils in thickness :—

Composition.	Structure.	Volts per mil.
(*a*) Manilla . . .	Normal cable paper	480
(*b*) Chemical wood (Sulphate process) . . .	Normal cable paper	470
(*c*)†Chemical wood (Sulphate process) . . .	Specially calendered	560
(*d*) Cotton	Finely beaten	360

Reverting to the question of the relative functions fulfilled by the components of the heterogeneous dielectric constituted by impregnated paper, the work of Malclès ‡ and Pungs § tends to show that conduction in oil is due to ionic travel

* Maxwell and Monkhouse ("Insulation of Electrical Machinery," *Electrician*, vol. xciv., No. 2450, 1925) found cotton paper superior to papers of other fibrous composition when tested in oil, but gave no information bearing on structure or manufacturing history. Their results regarding density tend to confirm the author's statement above.

† (*c*) was from the same " making " of paper as (*b*). Experiments connecting this increase of breakdown voltage with Del Mar and Hanson's results (see following page) would be of interest.

‡ *Comptes rendus*, 1910, vol. 151, p. 63. § *Archiv. f. Elektr.*, 1912, vol. 1, p. 329.

rather than to mere ionic displacement. Malclès' theory in explanation of phenomena which he found to occur when a condenser having a dielectric of petrolatum (petroleum jelly) was charged and discharged, was that the free ions were mobile when the petrolatum was liquid, and restricted when it was solidified. Pungs' work on dielectric losses in transformer oil appears to lend support to this theory, while its logical application to cable work has been the subject of experiments by Del Mar and Hanson,* in which sheets of paper were placed between electrodes immersed in oil. The breakdown voltage of the combination was found to increase as more sheets of paper were introduced, in spite of the fact that—on account of the higher specific inductive capacity of the paper—the oil would be more highly stressed as more sheets were added. Comparison of this result with the well-known Fessenden † experiment tends to confirm Malclès' theory, and to emphasise the importance of preventing the establishment of a stream of free ions in a dielectric.

With regard to the composition design of impregnating compounds, it will already have been appreciated from the electrical results obtained on various types of compound, shewn in Fig. 30, and the comments thereon, that physical properties have an important bearing on this matter. In a general way—in a given compound—variation in electrical properties appears to follow variation of physical behaviour over a given range of temperature, although chemical composition and molecular structure determines the nature of the variations as well as the specific values.

So far, only the fringe of this important matter has been touched on, and a vast amount of work remains to be done in co-ordinating these and other relations, and utilising them to the best advantage in dielectric design and manufacture.

As an example, bearing on such utilisation, the relation stated by Clark and Shanklin to exist between capacity and specific gravity (previously referred to) may be more important from the manufacturing point of view than at first sight appears; for, although specific gravity *per se* is of little moment, it has, in a given substance, a relation to viscosity.‡

Now the viscosity of a compound, and the manner of its variation over a range of temperature is of great practical importance to the cable-maker, bearing as it does on the twofold matter of getting the impregnating medium satisfactorily into place and its retention under subsequent working temperature conditions.

It will be clear that no matter how desirable the electrical properties of a compound may be, the manufacturing requirements respecting viscosity at various temperatures must be, within certain limits, complied with in order to be of practical use.

It will thus be seen that the co-ordination and utilisation above mentioned require to proceed synchronously.

With regard to the purely physical aspect, the following diagram, Fig. 31, shews comparative viscosities over a range of temperature in terms of time in seconds for 50 cubic centimetres of various typical impregnating compounds (referred to

* *A.I.E.E. Journal*, vol. 41, p. 439. † *Trans. A.I.E.E.*, vol. xv., p. 140, 1898.

‡ A further relation (*i.e.* that of thermal resistivity to viscosity) is referred to under Dielectrics—Properties and Limitations (see p. 203).

under Paper (and Jute) Impregnating Compounds, p. 67), to flow through the orifice of a standard Redwood viscometer.*

Curve A relates to Glover's Diatrine as used in their prior impregnation process, which renders a high viscosity permissible at impregnation and gives maximum retention under working conditions.

Curve B represents a resin-resin oil compound containing 60 per cent. resin and 40 per cent. resin oil, while curve C refers to a corresponding compound con-

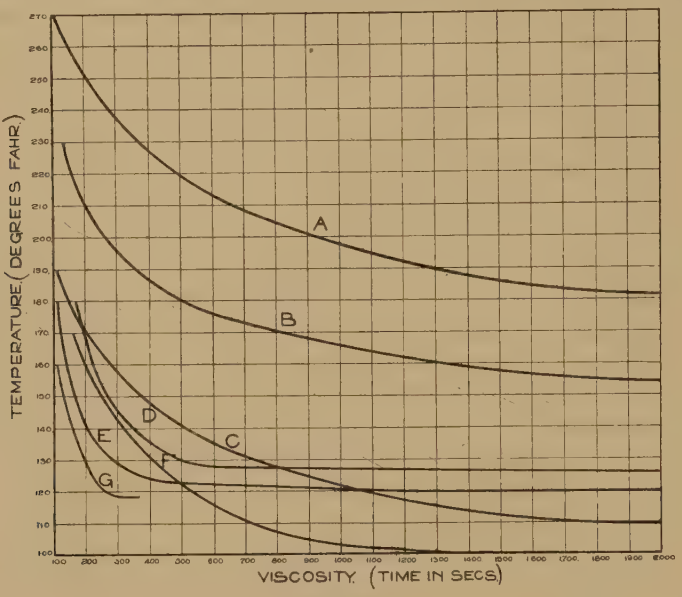

FIG. 31.

taining 40 per cent. resin and 60 per cent. resin oil. The compounds of this class generally used for the vacuum-pressure method of impregnating paper insulation after its application to the cable fall between the limits of these two curves.

It will be seen that curves B and C are practically parallel throughout. It may be noted that similar solutions or compounds in which mineral oil is substituted for resin oil give exactly similar curves. As showing the influence of the solute on the viscosity characteristics, it may be mentioned that—given the same solvents and proportions—bituminous compounds give appreciably steeper curves than resinous ones.

Curves D and E, relating to two grades of petroleum jelly (petrolatum), are shown to illustrate the difference in physical characteristics between this type of impregnating material and the " oil-solution " type, B and C. D refers to the grade known as " dark green," and E to that known as " red."

* As is well known, the absolute viscosity of a given fluid—assuming a perfect viscometer—is represented by the time in seconds of efflux of a standard quantity of the fluid through the orifice of the instrument, multiplied by its density (relative specific gravity) at the testing temperature. (Actually this value has to be multiplied by a correction factor which depends on the nature of the substance and the characteristics of the instrument.)

Curve F relates to heavy mineral oil, and is of interest as showing that whereas a true petroleum jelly (a residual product of distillation) assumes a consistency which is fairly constant below 120° to 130° F., the viscosity of a heavy mineral oil (a distillate) varies continuously with temperature, although at higher temperatures their viscosities may be of the same order.

Curve G shows the effect of mixing paraffin wax (130° F., M.P.) with the oil represented by curve F (80 per cent. oil, 20 per cent. wax). The change from the liquid to the semi-solid state is more pronounced in this instance, owing to the separation or crystallisation of the wax, and as a consequence the mixture passes out of the range of the Redwood viscometer at a temperature in the neighbourhood of 120° F.

It will be seen that little difference exists between the usual types of impregnating compound at the higher temperatures (representing impregnating conditions), low viscosity being a manufacturing requirement. The viscosity at working temperatures of the cable, which should, on the other hand, be high, is more or less a compromise between what is necessary or desirable at impregnating temperatures and at the same time attainable in the cable at working temperatures, with due regard to electrical properties.

This point is intimately connected with a manufacturing matter to which reference is made under "Manufacture," Vol. II, and which concerns the question as to whether the paper should be impregnated before application to the cable or impregnated *en masse* after the complete thickness of paper is built up on the conductor. In the latter case, another physical effect comes into consideration, viz., the tendency for a compound to become dialysed in the course of its diffusion through an appreciable thickness of paper. Some such action certainly does occur: resins, waxes, and, to a certain extent, bituminous components show a tendency to behave as crystalloids and to separate out from, or at any rate to penetrate less quickly than the oils or other colloidal ingredients of the compound. With the comparatively large thicknesses of dielectric which the high working pressures of the present day demand, this effect is naturally accentuated.

It has been suggested that this dialysis effect might, by suitable selection of ingredients, be taken advantage of to "grade" the dielectric; but apart from the fact that—with materials in use at the present time—the tendency would be to grade in the wrong direction, the wall of paper, being composed of superimposed strips, offers paths between the strips which are capillary rather than dialytic in character (in other words, impregnation is partly by percolation and partly by diffusion), and therefore the grading would not be uniform in a radial sense.

Subsequent diffusion or rearrangement of dielectric components under electric stress such as should theoretically occur, whereby substances of lower specific inductive capacity tend to move to parts at steepest potential gradient, has not been detected in ordinary cable practice, so far as the author's observation goes.

In addition to the general chemical requirements previously mentioned as applying to all types of dielectric (p. 164) a particular set of conditions (experimentally investigated a few years ago by the author) apply to impregnated paper

dielectrics, and link up their chemical and electrical properties in a peculiar way. Primarily, this matter relates to the great ease with which at certain critical temperatures the usual components of impregnated paper dielectrics are decomposable by simple destructive distillation with production of water, which, by reason of its association with other products of decomposition, is usually of an acid character. These critical temperatures are comparatively low, as shown below.

Materials.	Approximate Critical temperature.
Resin	670° F.
Bitumen, Native Mexican	350° F.
Bitumen, Gilsonite type	390°–410° F.
Resin Oil	320° F.
Mineral Oils	No moisture produced.
Cerasin Wax	No moisture produced.
Paper, unimpregnated	300° F.
Paper, impregnated with resin-resin oil compound	300° F.
Paper, impregnated with compound containing most of the above materials	300° F.
Asbestos	325° F.

Secondarily, the moisture produced is condensed on the interior of the lead sheath, or even before it arrives there (depending on the seat of the heating effect and the temperature distribution in the cable), and becomes absorbed by the contiguous undecomposed paper, forming an electrically weak path through the dielectric which under stress will again tend to heat up and produce more water.

This cumulative effect undoubtedly enters into the " mechanism " of breakdown of paper dielectrics under high electric stress, and in conjunction with differences shown in the above table, may help to account for observed differences in the rate of increase of dielectric loss between paper dielectrics containing different kinds of impregnating compound when approaching final breakdown.*

The total quantity of water producible at the critical temperature naturally varies considerably in different materials, but it will be clear from the foregoing that the use of impregnating materials which do not produce water as a product of distillation to the exclusion of those which do, will not prevent the risk of formation of water under conditions of local overheating, because the paper itself is the most susceptible component from the point of view of critical temperature.

COMPOSITION DESIGN OF VARNISHED CAMBRIC DIELECTRICS

It has been noted under " Insulating Materials " (p. 103) that varnished cambric depended on the surface films of varnish for its electrical properties, and

* That water is producible by decomposition (destructive distillation) of such substances is of course a well-known chemical fact; but the comparative ease with which it can be produced (*i.e.* at comparatively low temperatures and in proportions which may affect the electrical properties of the dielectric long before it is charred or destroyed) has not previously been appreciated.

that impregnation was avoided because it militated against the desired chemical stability of the finished product. Further, that the elimination of moisture from the fabric—at least, to the extent necessary for " non-breathing " conditions such as obtain in cable insulation—is always problematical, and the correction of this deficiency by the cable-maker, difficult. It will therefore be fairly evident that this material can never on account of its heterogeneous structure, follow impregnated paper into the field of high dielectric stresses entailed by high working pressures.

The requirements regarding the composition of a complete cable dielectric of varnished cambric are, of course, generally similar to those which apply in the case of an impregnated paper dielectric, in that it should consist of layers of moisture-free fibrous material, treated with insulating substances, and having the capillary spaces between the surfaces of the layers and the spiral passages between the edges of adjacent convolutions of each strip of material efficiently filled with compound. In the paper cable this filling is accomplished by the compound with which the dielectric is impregnated, but, clearly, this cannot be so in the varnished cambric cable. Primarily, the function of the filling compound in the latter was to facilitate the sliding of the layers over one another when the cable was bent, as indicated by the term " slipper," applied to it in America, where this type of cable originated. More recently, some specifications issued in that country have stipulated that this compound is to have the same specific inductive capacity as the varnished cambric —an impracticable requirement so far as present-day available materials are concerned, and one which is quite out of focus with the heterogeneous character of the material, to which allusion has been made above.

Physically the requirements are that the filling compound shall be sufficiently viscous to remain in place at the highest working temperatures to which the dielectric is likely to be exposed and to retain at low temperatures sufficient " greasiness " to allow relative movement of the layers of varnished fabric when the cable is bent or moved. Chemically it must be of such composition as not to have any injurious action on the varnish films with which it is placed in contact. This point does not seem to have received adequate attention in the past, judging from the fact that mixtures of common resin with resin or mineral oils are frequently found in different makes of varnished cambric cable and are also mentioned in published descriptions thereof.

The author prefers to use a mixture of heavy mineral oil with a suitable proportion of wax, which meets the chemical and electrical requirements, and is, at the same time, easily adjustable—by varying either the proportion or the composition (and consequently the melting-point) of the waxy constituent—so as to possess the physical properties required for certain ranges of temperature. Curve G (Fig. 31) shews that this type of filling compound is an eminently desirable one from the physical aspect.

COMPOSITION DESIGN OF RUBBER DIELECTRICS

The standard British practice in the construction of rubber insulation, originating from the construction devised by Hooper in 1860 and—as noted in Chap. I.—continued up to the present time, consists in applying a layer of pure rubber directly over the conductor, and superimposing two layers of vulcanised compound rubber thereon.

The inner of these compound rubbers was originally called the " separator " and the outer the " jacket," and to some extent these terms still survive, for example, in some Government specifications.

It is of interest, not merely from the historical point of view, but from the design aspect, to briefly and critically consider the functions of these various layers. It may even be permissible to speculate, in the light of our present knowledge, as to how the construction originated. The probabilities are as follows :—

The desirability of using vulcanised rubber in place of the pure rubber which had previously been employed for cable-insulating purposes would arise from the necessity of providing permanently waterproof insulation, which pure unvulcanised rubber was not, its absorption of water being very appreciable.

The troubles attending the provision of a sound covering of vulcanised rubber would be very considerable, and moreover, would be difficult to diagnose and remedy. They would include faults due to foreign substances and imperfections in the vulcanising compound sheet or strip, difficulties in applying the covering to the wires, and trouble through the action of sulphur on the wires or of imperfectly tinned copper on the rubber.

The interposition of a layer of pure rubber between the vulcanising rubber and the conductor would not only tend to protect the latter from the action of sulphur but would also help out the weaknesses of the vulcanised rubber in various ways. A further result of efforts to keep sulphur as far removed from the conductor as possible would appear in its reduction to a minimum in the first layer of compound rubber, while the outer layer could be more fully vulcanised and thereby chemically and physically improved even at some sacrifice of its insulating properties.*

Whether the foregoing accurately represents the evolution of this construction or not, it is certain that even in the early part of the present century it was commonly accepted that the function of the pure rubber was to " prevent access of sulphur to the conductor " (this expression is still in use in certain specifications) and to improve the insulation resistance ; and further, that the first layer of compound rubber was vulcanised rubber insulation proper, while the second functioned as chemical protection and physical reinforcement thereto.

* It is of interest to note that the arrangement of " pure, separator and jacket " would be in accord with a scientific design to obtain high values of insulation resistance, the latter being, in the early days, the main criterion of quality. Such design would call for the material of highest insulativity to be placed nearest to the conductor, and for succeeding layers to be arranged in descending order of insulativity.

From the point of view of dielectric stresses, however, the " pure, jacket and separator " construction constitutes inverse grading.

The original reason of the colour of the inner layer being white or drab and the outer black or grey may have been purely incidental, the latter being the result of the use of litharge as an accelerator, and the former being due to the use of zinc oxide.* In any case, the colour distinction is still adhered to, although in well designed compounds the degree of vulcanisation is to-day such that both layers have approximately similar chemical and physical properties.

It must be pointed out, however, that the above-mentioned conception of the function of the pure rubber, *i.e.* to " prevent access of sulphur to the conductor," is entirely erroneous.

So far from preventing it, not only does sulphur reach the conductor during vulcanisation, as evidenced by the formation of sulphides of tin on tinned copper conductors, but, as pointed out in reference to rubber compounding ingredients (" Insulating Materials," p. 95), in accordance with the physical laws governing the movement of crystalloid substances in a colloidal matrix, the free sulphur, which is always present to some extent in vulcanised compounds, is subsequently—in the cold—forced to pass through it to the inner surface of the dielectric, *i.e.* into actual contact with the conductor.† Moreover, when this migration is complete and equilibrium of the forces which give rise to it is reached, no direct harm results either to the conductor or the rubber unless the abnormal condition arises of moisture finding access to the inner surface of the dielectric, in which case sulphuric acid is formed and the conductor is attacked, with secondary effects on the rubber. (This latter faulty condition need not be further considered here because it has no direct bearing on design.)

Curiously enough there is another fallacy closely connected with the foregoing, relating to the function of the tin coating which is always applied to copper wire intended for use in rubber cables; this is that the tin is there to prevent the action of sulphur on the copper.

True, it does do so, but sulphide of copper has *per se* no deleterious action on rubber, and consequently if this were the whole truth there is no apparent reason for any definite and expensive measures to prevent its formation. The real truth is that all the trouble which arises from the juxtaposition of dielectric and conductor materials is due to the action of copper on rubber.

In this connection the following extract from the author's Paper on " Cables " (*l.c.*, *ante*), p. 71, may be of interest :—

" In stranded conductors of high-grade rubber cables it often happens that the vulcanising conditions result in the formation of two sulphides of tin, the stannic sulphide, Sn_2S_4, on the wires in contact with the rubber, giving the golden tint but not interfering with the metallic lustre of the tin, and stannous sulphide, Sn_2S_2, on the interior wires of the strand, giving a greyish coloration. The blackening due

* In old specifications the inner layer is called the " zinc separator."

† It is noteworthy that in high-grade (*i.e.* strongly colloidal) rubber compounds the sulphur crystals—or agglomerates of crystals—are large and well separated, whereas in low-grade vulcanised rubber compounds and vulcanised bitumen (*i.e.* materials having comparatively weak physical structure) the crystals are small and uniformly distributed.

to sulphide of copper formed on exposed copper is readily distinguishable from discoloration due to tin sulphides. Neither the tin sulphides nor the copper sulphide are in themselves at all harmful to rubber. The blackening due to copper sulphide must, however, always be considered a detrimental feature if in contact with the rubber, as the film of copper sulphide is not sufficient to protect the rubber from the catalytic action of the copper, and may, therefore, be considered as an intimate admixture of copper oxide and copper sulphide.

"A rough demonstration of the fact that the sulphides of tin and copper are harmless to rubber, and that the contact with metallic (and, of course, oxidised) copper is the origin of the deterioration in question can be made very simply by placing small quantities of copper oxide and the sulphides of tin and copper side by side on a sheet of pure rubber and warming for a few hours. The rubber under and around the copper oxide will be rendered soft and tacky, but will be unaffected where in contact with the sulphides of tin and copper. Generally speaking, all the above-mentioned deterioration effects are accentuated by heat."

It follows that efficient tinning is of the highest importance.

It further follows that, given efficient tinning, access of sulphur to conductors is of minor importance ; and as it has been shown that pure rubber does not prevent such access, it also follows that its remaining function (previously referred to) of improving the insulation resistance of the dielectric is the only *raison d'être* of the pure rubber layer ; so that if the vulcanising rubber can be applied sufficiently soundly, the use of pure rubber becomes of still further diminished importance.

An approach can be made to the preservation of the tin coating of the conductors from discoloration by the formation of sulphides (whether the pure rubber layer is used or not) by reducing the amount of free sulphur in the vulcanised compound rubber, for example, by the use of accelerators.

The selection and proportioning of the ingredients of the compound rubber is a complex chemical matter because, as already noted, various optima in the way of properties have to be attained and balanced to the utmost general advantage. As we have seen, a great deal depends on the molecular structure of the vulcanised rubber, and beyond such evidence as has already been quoted to the effect that a molecular structure which gives good physical characteristics and chemical stability does not necessarily give good electrical properties, little is known, and that little only indirectly.

Now, chemical stability is practically as essential as electrical efficiency, because directly chemical change arises the electrical properties are affected, not only by the molecular alteration, but also by the modification of physical structure ; and such changes are practically always in a detrimental direction. Again, regarding electrical properties only, one of them, say specific insulation, should not be attained at the expense of another such as dielectric strength ; and while material which is inert to the vulcanising reaction, such as French chalk, is excellent for attaining the former property, a better physical structure of the vulcanised compound and rather greater dielectric strength is obtained by employing a substance

which does react to some extent in the process of vulcanisation, such as zinc oxide. Hence a judicious mixture of the two is frequently used. For simple loading, with no beneficial effect on the general properties of the vulcanised rubber compound, but fulfilling certain commercial requirements regarding the production of the cheaper grades of insulation to the best technical advantage, whiting, lithopone, and the " zinc white " class of " fillers " are used.

With regard to the proportioning of vulcanising and accelerating ingredients, the sulphur, which, as stated under " Insulating Materials," p. 90, is the only substance used in cable rubbers for vulcanising purposes, is proportioned to the rubber content with due allowance for the fact that an excess has to be used over that which is required to correctly vulcanise the rubber. It usually varies from 4 per cent. to 6 per cent. (or thereabouts) of the weight of the rubber contained in the compound,* according to the vulcanising conditions and the proportions of the accelerators or " sulphur carriers " employed.

From the point of view of adjustment and control of all the properties which have been referred to, the latter are the most valuable compounding ingredients.

Their apparent effect is of a physical character, although, as mentioned under " Insulating Materials," p. 94, there appears reason to suppose that the root cause of physical variations (demonstrated by differences in electrical behaviour when the composition of the accelerator is varied in a given compound) is of a chemical nature.

This relation is exemplified by the results of a series of experiments carried out some years ago by the author, in which the absorption of air by samples of vulcanised rubbers containing varying proportions of accelerators under certain constant conditions of test was taken as a comparative criterion of physical structure.

The conditions of test were as follows :—

Each sample was vulcanised in the form of a solid ball having a volume of 36 cubic centimetres and then subjected to air pressure at 500 lb. per square inch for one hour.

The air absorbed under these conditions was slowly given up on releasing the pressure, and measured by displacement of water in terms of volume of air collected per 100 square centimetres of the surface of the sample.

The curves (Fig. 32) relate to two 50 per cent. rubber compounds in one of which magnesia was used as an accelerator, and in the other litharge, the normal proportion of each being represented by x. The compounds were otherwise similar.

In the former, to which the curves A and C relate, the proportion of magnesia was increased in steps up to $x+5$ per cent., and in the latter (curves B and D) the litharge was similarly increased up to $x+15$ per cent., these percentages (reckoned on the rubber content of the compounds), being approximately those required to produce minimum absorption under the conditions of test.

* Specifications of some British Government Departments stipulate a maximum of 2 per cent. (on the total compound) in the case of 40 per cent., and 3 per cent. in the case of 60 per cent. rubber compounds.

Curves A and B record the air collected, each point on the curves being the mean of four tests.

Curves C and D show the percentage reduction in air absorbed corresponding to the increasing proportions of accelerator.

It will be observed that while the volume of air absorbed is less in the case of litharge, the rate of reduction of air absorbed with increasing proportion of accelerator is, as might be expected on chemical grounds (heat of reaction), more rapid in the case of magnesia. These results are in line with what is known regarding the effect of these accelerators on physical (absorption of water), and consequently electrical properties, and tend to establish connection between them

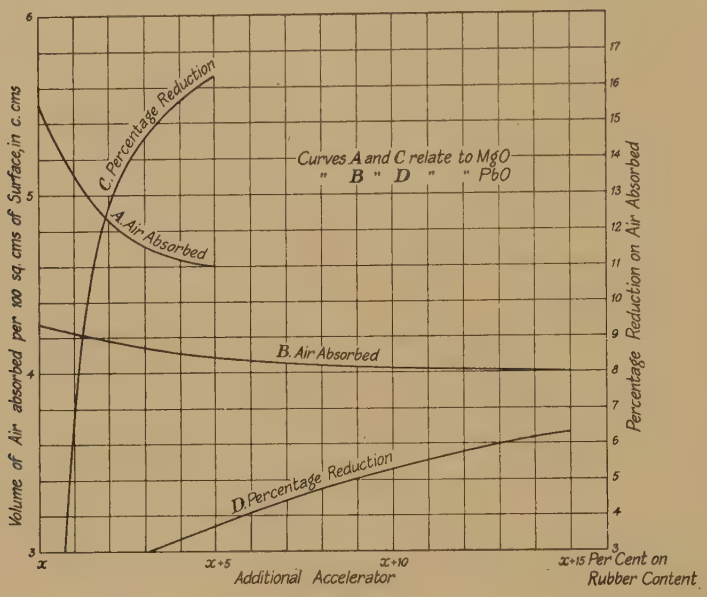
Volume of Air absorbed per 100 sq. cms of Surface, in c. cms
Percentage Reduction on Air Absorbed
C. Percentage Reduction
A. Air Absorbed
Curves A and C relate to MgO
" B " D " " PbO
B. Air Absorbed
D. Percentage Reduction
x
x+5
x+10
x+15 Per Cent on Rubber Content
Additional Accelerator

FIG. 32.

and molecular structure, which in turn is dependent on the mechanism of the vulcanising reaction.

Here we may note a further point of interest in connection with the different effects obtained from the use of these two inorganic accelerators. If magnesia is used in the inner (drab) layer, and litharge in the outer (grey) layer of an ordinary pure and vulcanised rubber dielectric, the insulation resistance characteristics of the complete dielectric are of the same order as though magnesia were used in both compounds, even though the proportion of magnesia in the inner layer is less than half that of the litharge in the outer layer, indicating that the more powerful accelerator determines, or at least largely influences the physical structure of the whole dielectric.

A further interesting result was obtained from a series of tests of the same character on balls made from rubber compounds of the same type as regards mineral

matter containing from 30 per cent. to 60 per cent. of rubber, in each of which litharge was employed as accelerator; the proportion of litharge varied in a direct ratio to the rubber content. It will be observed from Fig. 33 that the air absorbed increased with increasing rubber content. Analysis of the details, however, shewed a decreased air absorption with increasing amounts of litharge, and a further experiment carried out to confirm the latter point shewed only 2·8 c.cs. of air absorbed per 100 sq. cms. of surface exposed in the case of a compound composed of 65 per cent. rubber, 30 per cent. litharge, and 5 per cent. sulphur.

Reference at some length has already been made ("Insulating Materials," p. 94) to organic accelerators. Commercial scale tests carried out by the author show clearly that differences of the same kind as those instanced above which occur in the case of inorganic accelerators also apply to organic, *i.e.* one which gives good results from the point of view of physical characteristics does not necessarily give correspondingly good electrical results.

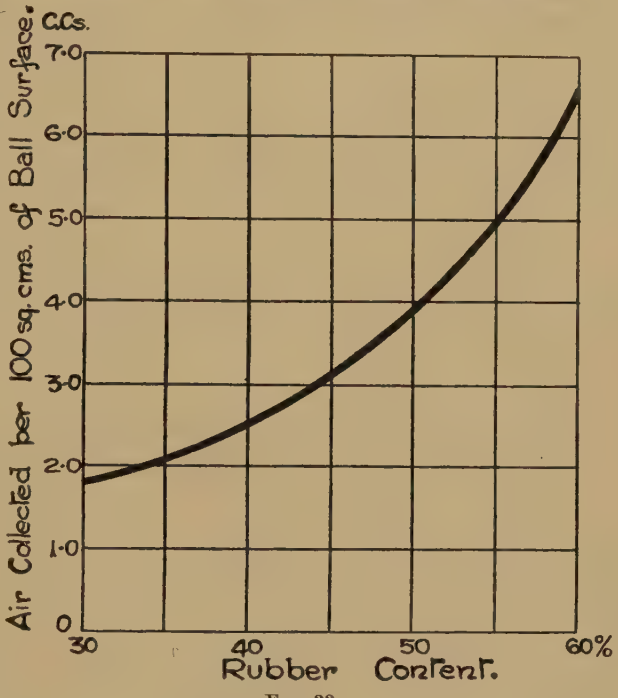

Fig. 33.

The author's experience, taking into account manufacturing and economic factors as well as technical results, is rather in favour of paranitrosodimethylaniline, without the use of any inorganic accelerator.

It is of interest to note that the electrical characteristics and (so far as absorption of water is concerned) the physical properties of a given grade of vulcanised insulating rubber compound are not appreciably altered by the substitution of paranitrosodimethylaniline (in suitable proportion) in place of litharge.

In illustration of this comparison the diagram (Fig. 34) shows the results of daily tests of insulation resistance taken over a period of thirty-seven weeks on two lengths (B and C) of 7/·036 inch vulcanised rubber insulated wire in which this organic accelerator was employed, and one length (A) in which the accelerator used in the (otherwise similar) rubber compound was litharge, each point plotted being the average of the week's tests.

The lengths of insulated wire were 220 yards in each case, and they were kept immersed in water for the whole of the test period. The behaviour of the length in which litharge was employed was known to be normal.

The electrostatic capacity was practically identical in the three lengths. After the insulation resistance tests were completed, a dozen breakdown tests were made on each length. The breakdown voltages were of the same order in each case, and the uniformity of the values was not less in the lengths containing the organic accelerator than in the length containing litharge. Heat tests indicated that the former was at least as good as the latter from the point of view of durability.

Given a rubber dielectric which is suitably designed from the electrical and mechanical points of view, the " coefficient of vulcanisation " (a term originally introduced by Weber * to indicate the percentage relation of the sulphur combined with the rubber, or " sulphur of vulcanisation " to the rubber content of the com-

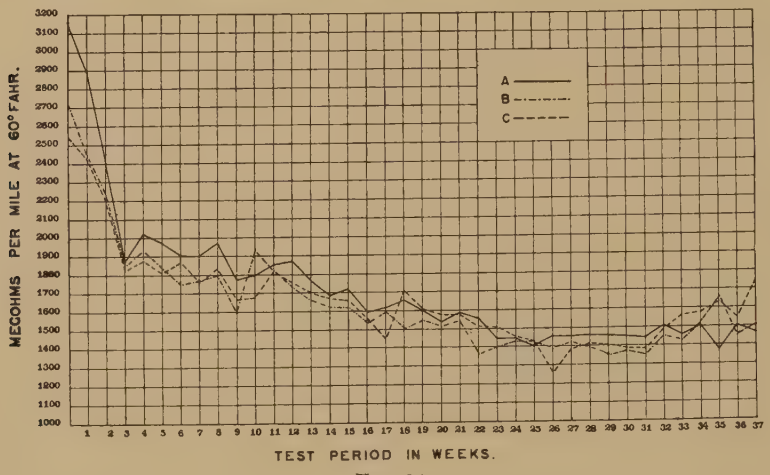

FIG. 34.

pound) forms a valuable criterion of general physical efficiency and chemical durability.

The actual value of this coefficient is dependent on, or at least affected by the total sulphur in the rubber, the kind of rubber, the character and proportion of accelerators used, the conditions of vulcanisation, etc., and it is therefore clear that for a given set of these factors, such value should lie between certain limits to ensure correct vulcanisation.

The specific maximum and minimum values should, for a given grade of rubber compound, be determined in conjunction with tests on tensile strength and elongation in the course of adjustment of the vulcanising conditions.

Generally, in the class of rubber compounds used for cable purposes, the coefficient of vulcanisation is of the order of 2·75 per cent. to 4·0 per cent., but is, of course, variable with different makers' practice.

* Weber, " The Chemistry of India-rubber," 1902.

COMPOSITION DESIGN OF VULCANISED BITUMEN DIELECTRICS

As vulcanised bitumen, regarded as a dielectric, is a single substance—unlike paper and rubber, which respectively have impregnating compounds and filling and vulcanising ingredients added to or incorporated in them—the data given under "Insulating Materials," p. 99, really embraces composition design.

When considering it under this heading, its physical properties were, for the sake of convenient explanation, compared with those of rubber. From the point of view of its composition design as a dielectric it may be well to bear in mind that the parallel with rubber is still closer in other directions.

For example, its vulcanisation is of the same general character as that of rubber. It is brought about in the same way, *i.e.* by combination with sulphur at a critical temperature (or within a certain range of temperature), and changes of a broadly similar physical character are produced in the material as a result of the vulcanising reaction.

As a dielectric, however, it differs from rubber in that it is vulcanised before application to the cable, as it is not a feasible manufacturing proposition—owing to physical deficiencies of the unvulcanised material—to apply it before it is vulcanised.

No additional vulcanisation is carried out, as a rule, after the application of the vulcanised bitumen to the conductor, unless the somewhat unusual method is adopted of sheeting the material by calendering it, and lapping it in strip form on the conductor, in which case the layers can only be made homogeneous, or approximately so by further vulcanisation.

The general parallelism with rubber as regards vulcanisation holds good from the aspect of degree of vulcanisation. For a given set of conditions embracing ingredients on the one hand and resultant physical properties of the finished material on the other, the coefficient of vulcanisation should be as high as possible. This tends—as in vulcanised rubber—to ensure maximum chemical stability, the primary object being to leave no vulcanisable material uncombined with sulphur, *i.e.* with possible tendencies to behave under conditions to which it may ultimately be exposed in a different (less inert) manner to the main body of the material.

As indicated under "Insulating Materials," p. 100, having determined the best combinations and proportions of ingredients and the best degree of vulcanisation, physical tests are, in the author's experience, the most convenient check on general properties.

For the purpose of adjusting or balancing these properties, mineral matter (of the character of the "fillers" used in rubber compounds) is incorporated in vulcanised bitumen by some cable-makers, and in some cases proportions up to 15 to 20 per cent. have the effect of procuring a certain degree of toughness at the expense of course of resilience, but with overall beneficial results. Larger proportions, while apparently producing a more solid dielectric, are disadvantageous *

* See tests by Blount. Atkinson and Beaver's Paper, "Some Points on the Selection of Electric Cables," *The Electrician*, vol. 54, p. 702, 1905.

from the point of view of resisting and recovering from deformation under mechanical stresses.

Moreover, there appears to be a critical point in respect to the proportion of such mineral matter at which the selective action of extraneous deteriorating influences is at a minimum, *i.e.* where the structure of the vulcanised bitumen is filled without undue exposure of the filling substance.

For resistance to certain hydrolytic influences a special "colloidal filling" is used by one firm of cable-makers * for vulcanised bitumen dielectrics for use in the tropics and in other special situations where elevated temperatures (which constitute one factor in this type of deleterious influence) are likely to be encountered. This is described as follows in the author's Paper on "Cables" (*l.c.*, *ante*).

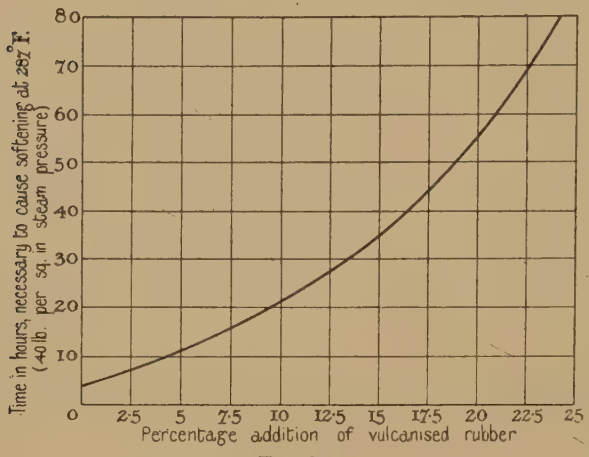

FIG. 35.

"Some form of colloidal filling having the requisite physical properties to allow of its incorporation with the vulcanised bitumen, of such composition as not to be capable of decomposition by hydrolytic action, and which at the same time would exert a maximum protective effect when present in small proportion, was clearly the ideal. After much experimental work it was found that high-grade vulcanised rubber could be treated in such a manner that it would fulfil the requirements as regards incorporation with vulcanised bitumen, and would in addition exert a surprising degree of protection against hydrolytic and selective action, even when used in small proportions. In fact, that was apparently some kind of mutual protective action, because the resistance to softening under the steam-pressure conditions previously described was greater in the combined substance than in either of its components.

"Fig. 35 records graphically the results of a series of tests on the degree of protection afforded by various percentages of vulcanised rubber when subjected to steam at a pressure of 40 lb. per sq. in., the softening periods being determined by observation. It will be seen that the addition of about 6 per cent. of vulcanised rubber trebles the time required to produce the softening, and that up to about 12 per cent. the time is proportionately increased. When larger proportions are used the curve rapidly becomes steep, and at 40 to 50 per cent. the protection from softening effects appears to be infinite. Remembering that the softening action only occurs under faulty conditions and requires five or six years to develop to a troublesome stage, the protection afforded by 5 to 10 per cent. of the

* Glover's "Cloida" bitumen cables, Patent No. 9554/1914, Beaver & Claremont.

rubber substance would appear to be ample under the worst conditions of practice."

The vulcanised bitumen type of dielectric was originally employed in conjunction with an impregnated jute covering lapped on the conductor, the object being, according to the specifications of some large cable users, "to prevent decentralisation." Later practice, extending to the present day, was to substitute impregnated paper for the jute "separator," as it was termed. Various advantages were claimed for this "paper leadless" combination, one of which—cooler running as compared with vulcanised bitumen alone—being open to some question in view of the similarity of the heat conductivities of the two materials.* Other advantages, however, such as the ability to employ a more mechanically and electrically efficient dielectric for extra high tension purposes, when a vulcanised bitumen sheath is required, are very tangible.

For pressures up to about 6000 volts, however, present-day manufacturing practice permits the employment of vulcanised bitumen alone if conditions render it desirable to employ a complete non-hygroscopic dielectric.

As a final parallel to rubber it may be mentioned that—for the same reason—it is necessary to tin the copper conductors with which the vulcanised bitumen may be placed in contact.

* See page 200, Design, Properties, etc.

CHAPTER IX

PROPERTIES AND LIMITATIONS OF DIELECTRICS

ELECTRICAL PROPERTIES

The great majority of published tables of figures relating to the electrical properties (dielectric strength, specific inductive capacity, and specific insulation) of insulating materials, such as paper, resin, oils, waxes, glass, porcelain, mica, rubber, ebonite, bitumen, etc., are devoid of any practical meaning. The chief reason for this is lack of data with regard to the composition, grade or quality, commercial description, or other means of identification. In some cases sufficient reference to composition, origin, and method of production may be made in the original researches on the materials, but when the figures are quoted and requoted in reference books, it frequently happens that all trace of precise identity becomes lost, and the values ascribed to them become correspondingly indefinite and meaningless.

For example, from the immediately preceding subsection of this work it will be particularly obvious that specific values for " rubber "—even apart from the fact that frequently the elementary distinction between pure and vulcanised rubber is omitted—must be more or less futile.

With regard to some of the other materials instanced above, there are at least half a dozen grades, more or less commercially standardised, of resins and of waxes, such as paraffin. In resin oil and vegetable oils there are usually three or four commercial grades, representing various degrees of refinement. Of grades of mineral oil it may be said that " their name is legion." Porcelain and mica are by no means definite substances ; glass varies in composition and therefore in properties, and bitumen varies enormously according to its origin, etc.

It is therefore clear that if these facts are ignored or the values of properties stated without due reference thereto, such data can only be of limited value, and comparative rather than specific in character.

From the point of view of the cable designer and user, a further limitation of the usefulness of such figures is entailed by the fact that—as we have seen—dielectric materials are seldom single substances, but usually admixtures or combinations of them. While it is useful to obtain figures on samples of components of the combinations in convenient apparatus if they are simply physically united, as in the case of impregnated paper, and not chemically transformed, as in the case of vulcanised rubber, values for complete dielectrics should be determined from commercially manufactured cables.

It will be clear, for example, in the case of impregnated paper, that there will be a considerable difference between the results obtained from tests on it in the form of sheets (tested between plates), and those from the same material in the form of a dielectric applied to a conductor. In the latter case factors are introduced such as spiral application in strip form, with gaps between the convolutions, and the staggering of successive strips ; *i.e.* differences in the form of the material. There is also a

difference in its disposition, *i.e.* it is laid upon a surface of small curvature with—in the case of a stranded conductor—a corrugated surface.

These factors tend to affect the apparent values, more or less, of all its electrical properties.

With regard to tests on component materials, apparent values are affected to a marked extent by the form of apparatus, the shape and dimensions of the electrodes, and the thickness and preparation of the specimen.

The effect of the form of apparatus on its heat-dissipating constant, and the general relationship between very small and moderate thicknesses, is well known.

The mathematical relation between the breakdown pressure of specimens of given thickness, tested between spheres of given diameter embedded therein, and their dielectric strength is also well known; but such electrode conditions can only be applied to liquids and liquefiable or mouldable solids, and not to laminated materials like dry or impregnated paper.

The relation in the case of flat plates is obviously much less definite, apart from errors due to difficulties in the preparation of the specimen.

Values for properties such as capacity and power factor are even more difficult to determine, on account of the delicacy required in making the tests; the above-mentioned methods are quite inadequate, and it becomes necessary to construct condensers with the material to be tested as dielectric. Insulated cables are the most convenient form of condenser for tests on complete dielectrics, while components have to be made up into a series of plates or accommodated between concentric cylinders to attain an adequate area.

Enough has probably been said to emphasise the difficulty of obtaining figures which can reasonably be regarded as specific values, or which are of practical use except in the hands of an expert designer.

In the following Table, No. XIII, a few approximate values are given relating to the electrical properties of the standard dielectric materials, including the components of impregnated paper (dry paper and impregnating compound), and—for the sake of comparison—four other insulating materials which are not available for cable insulation.

The wide variation in certain of the values shewn calls for some explanation. For instance, in the case of vulcanised rubber, it should be noted that they relate to a range of "grades" of this material in which the rubber content varies from 30 to 70 per cent.

In the case of the power factor figures for impregnated paper, the wide range is not so much a matter of materials as that the values vary considerably with the electric stress if the impregnating process is not perfect and air spaces exist between the electrodes. Even assuming that the paper is perfectly impregnated some variation of power factor with electric stress will occur in multicore cables due to tangential stress effects. Dielectric power factor only becomes of outstanding importance in super-tension cables, in which high electric stresses are entailed; hence the difficulty of assigning a specific value is even greater than in other cases, especially in the absence of standard conditions of determining it.

TABLE XIII

Dielectric.	Dielectric Strength.		Relative Specific Inductive Capacity.		Specific Insulation Resistance.		Power Factor.		Remarks.
	K.V. per c.m.	Authority.	Air 1.	Authority.	Ω per Mile Cube.	Authority.	Cos Φ	Authority.	
Dry Unimpregnated Paper	43 91	S.H.E.E.*	1·7–2·6	S.H.E.E.	6,200	S.H.E.E.	·007	S.H.E.E.	P.F. is given as measured at 920 cycles.
	43 55	E. H. Rayner †	1·8–2·2	Coyle & Howe ‡					Rayner's tests were made on 11–15 mil thicknesses between plates. Diam. of smaller plate, 1″.
	59	Crompton & Co.†							
	59	Author							12-mil thickness between plates. Diam. of smaller plate, 5″.
Impregnating Compounds	280–300	Author			50,000–60,000	Author			Representing resinous types of compound suitable for impregnating purposes; *e.g.* mineral oil and resin compound, or vegetable and mineral oil, wax and resin, etc., compound. Tested between ½″ spheres, 60 mil gap, embedded therein.
Impregnated Paper	230[1]	Coyle & Howe	2·8–3·8	Coyle & Howe	5,000 (2,000–30,000)	Author	·009–·06 (·018 av.)	Coyle & Howe	[1] 6-mil dried and impregnated sheet.
	200[2]	Coyle & Howe	3·3	Author			·03 approx.	Still §	[2] Tests on cables.
	200	Author ‖	2·8–4·0	Clark & Shanklin ¶					Representing ordinary cable manufacture.
	300	Author **					·0072–·009	Author	Representing improved manufacturing methods for supertension work. Tests on cables.
							·005	Shrader	Tests in special apparatus on three layers of paper. Thickness, ·021 cm.
Paper and air space (as in Dry Core Telephone Cables)			1·5 1·7–1·9	Author Coyle & Howe	200,000	Author	·003	Fleming & Dyke ††	Fleming & Dyke's determinations of power factor values for various materials relate to telephonic frequency and pressure conditions.

Impregnated Jute	40–70	Coyle & Howe	3–4	Coyle & Howe	18,600	Coyle & Howe	·02–·03	Coyle & Howe	
Pure I.R.			2·4	Author	65,000–120,000	Author	·005	Fleming & Dyke	
Vulcanised I.R.	160–250	Coyle & Howe	3·0–5·5 4·6–6·0 2·8–6·1	Coyle & Howe Clark & Shanklin ¶ Author	30,000–75,000	Author	·028–·032 ·002	Coyle & Howe Fleming & Dyke	Clark & Shanklin refer to the values they give as 60 cycle relative permittivities, at 55° C. The author's values were determined by the ballistic method.
Vulcanised Bitumen	140	Coyle & Howe	4·5	Author	1,500	Author	0·12	Constable & Fawsett ‡‡	
Varnished Cambric	200–500 (in thin sheets) 160 (·24″ thickness instantaneous)	S.H.E.E. M. E. Tressler ||||	3·8–5·2 3·5–5·5	Clark & Shanklin S.H.E.E.	1,350–5,500	S.H.E.E.	·004–·2	H. W. Fisher §§	
Mica	400–5000	S.H.E.E.	2·5–5·9 5·5–7·5	S.H.E.E.	2·7–820	S.H.E.E.	·001	S.H.E.E.	
Glass	60–120	S.H.E.E.	5·5–10	S.H.E.E.	60–6,000,000	S.H.E.E.	·018	S.H.E.E.	
Ebonite	400–1500	S.H.E.E.	1·9–3·5	S.H.E.E.	6,000–6,000,000	S.H.E.E.	·005	Fleming & Dyke	
High Voltage Porcelain	90–120 ($\frac{1}{2}$ to $\frac{1}{10}$″)	S.H.E.E.	4·4–6·8	S.H.E.E.	600–6,000	S.H.E.E.			

* *Standard Handbook for Electrical Engineers.* (M'Graw-Hill Book Company Inc.)
† E.S.C. Report, No. 22.
‡ Coyle and Howe, *Electric Cables : Their Construction and Cost*, 1909.
§ Alfred Still, *Electric Power Transmission*, 1919.
|| Beaver, "Cables." *Journ. I.E.E.*, vol. 53, p. 61, 1914.
¶ Clark and Shanklin, "Single Conductor Cables for High-tension Polyphase Systems." *Proc. A.I.E.E.*, vol. 38, p. 663, 1919.
** I.E.E., Informal Paper, 1925.
†† Fleming and Dyke, "On the Power Factor and Conductivity of Dielectrics." *Journ. I.E.E.*, vol. 49, p. 323, 1912.
‡‡ Constable and Fawsett, "Distribution Losses in Electric Supply Systems." *Journ. I.E.E.*, vol. 32, p. 707, 1902.
§§ H. W. Fisher. *Proc. A.I.E.E.*, vol. 32, p. 2219, 1913.
|||| M. E. Tressler. *Proc. A.I.E.E.*, vol. 32, p. 2121. 1913.

The figures given in the Table are (unless otherwise stated) based on a temperature of 60° F., and in order to be of service in the design of cables, require to be supplemented by information as to variation with temperature.

Temperature coefficients not only vary for each material, but are of a widely differing order for each of the electrical properties referred to in the above Table.

For example, the variation of dielectric strength with temperature is quite small, and does not vary uniformly; whereas insulation resistance varies considerably.

It may be noted in passing that as the process of determining dielectric strength entails more or less heating in the substance under test, the exact values of temperature coefficients for dielectric strength are always open to some degree of doubt.

With regard to the variation of insulation resistance with temperature, the curve, Fig. 36, relating to a certain make of impregnated paper dielectric is taken from a Paper read by Mr Ll. B. Atkinson and the author (*l.c.*, *ante*). It may be taken as typical of practically all impregnated paper dielectrics.

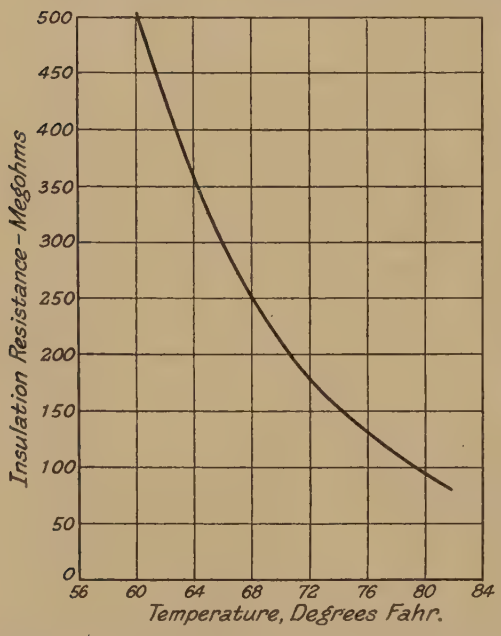

FIG. 36.—CURVE SHOWING RELATION BETWEEN THE INSULATION RESISTANCE AND TEMPERATURE FOR PAPER INSULATED CABLES.

It is of interest, in view of the consideration already given to the question of the relative functions of the paper and compound (p. 167), to note that both components have steep resistance/temperature curves. Roughly, for a rise of 20° F., from 60° F. to 80° F., the insulation resistance of the paper is reduced to about 50 per cent., and that of the compound to about 25 to 30 per cent. of the original values. The corresponding value for the combination represented by the impregnated paper does not appear to be closely related to these figures.

Fig. 37 shows the general order of the usually accepted insulation resistance temperature coefficients for impregnated paper, rubber, and vulcanised bitumen dielectrics usually accepted in British practice, although only those for rubber appear in official (Government Department) specifications.

It will be appreciated that the foregoing values for electrical properties, although not—by reason of the scope for improvement in materials—by any means final, are fairly definite and, apart from other properties, carry certain definite limitations.

For example, it is clear that for very high pressure alternating current work, where a combination of high dielectric strength, low electrostatic capacity, and small power factor is required, impregnated paper stands ahead of other types.

The first-mentioned property is a *sine qua non*, while capacity determines the important operating feature of " charging " or capacity current, and consequently the apparent power required to charge the line, according to the following well-known formula :—

$$\text{Charging current: } I_c = 2\pi f K E \times 10^{-6} \times l,$$

where f is the frequency, K the capacity in microfarads per mile, E the R.M.S. value of the voltage to which the line is charged, and l is the length in miles.

In the three-phase case the voltage between cores is E, and K_e is the " 3-phase working " or " equivalent star " capacity from each phase to neutral, and is approximately 1·2 times the value of K above mentioned; so that the charging current per mile for each core will be :—

$$I_c = 2\pi f K_e \frac{E}{\sqrt{3}} \times 10^{-6} \times l.$$

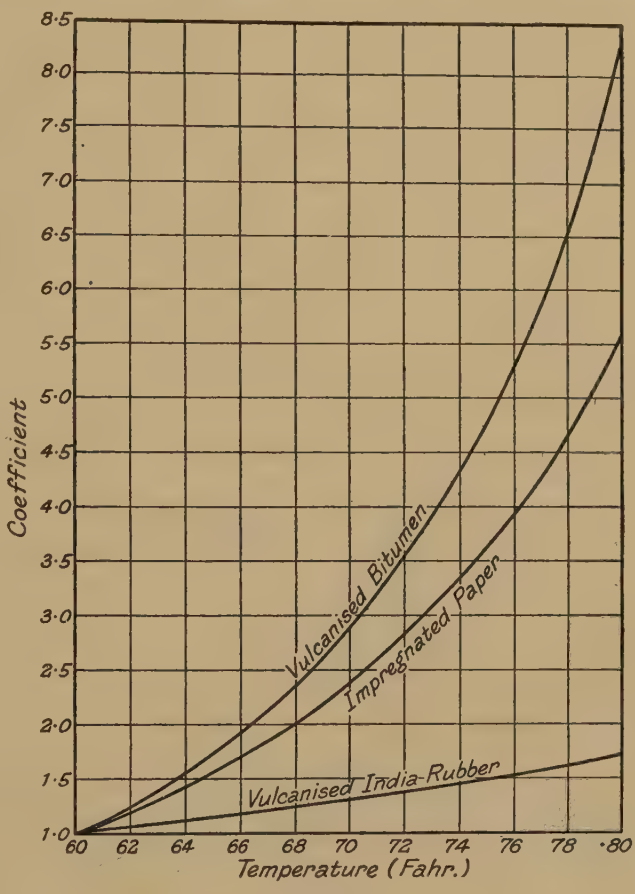

Fig. 37.

The whole of this charging current has, of course, to be provided for in the generating apparatus, and in the design of long lines at very high voltages the size of plant required to charge the line is a matter which has to be borne in mind. Not infrequently, schemes for the transmission of comparatively small amounts of power at very high voltages are found on investigation to be impracticable on account of the large proportion which the plant required for charging the line and supplying the line losses bears to the total plant. In many such cases it would be more economical to transmit at a lower voltage.

On large networks, of course, the charging current may, under favourable conditions, more or less neutralise the wattless current caused by the inductance of the apparatus connected to the system; in fact, condensers are frequently introduced into high voltage A.C. networks for this purpose.

The temperature co-efficient of electrostatic capacity is usually regarded as negligible in ordinary practice. Dry paper has a slight negative temperature coefficient. Reverting, however, to the previous notes on the relative properties of paper and impregnating compound, it has been shown (*vide* Fig. 30) that considerable variation with temperature may occur in the latter component, so that there is a possibility that a badly designed compound may produce undesirable characteristics in the dielectric material in its final form.

The significance of the requirement of low-power factor, above mentioned, lies in the fact that whereas the main component of the charging current is " wattless," being 90° in advance of the voltage wave (and its power product therewith being always zero), the imperfection of the condenser constituted by the dielectric causes it to lead by less than 90°.

The cosine of the angle between charging current and impressed voltage is the power factor of the dielectric, and the watts corresponding to this in-phase component of the charging current constitute the dielectric loss. Thus :—

$$W = E \times I_c \times \cos \phi,$$

where W represents watts lost in the dielectric, E is the impressed voltage, I_c is the current flowing into the cable, and $\cos \phi$ is the power factor of the dielectric.

The total dielectric loss in the 3-core cable will be :—

$$\text{K.W.} = 3 \times \frac{E}{\sqrt{3}} \times I_c \times \cos \phi \times 10^{-3}$$

$$= \sqrt{3}\, E \times I_c \times \cos \phi \times 10^{-3},$$

where E is the R.M.S. voltage between phases, and I_c is the charging current flowing in each phase, or into each core of the cable.

This is, of course, a true power loss which is continuously incurred while the cable is alive, whereas the K.V.A. corresponding to the larger component, in quadrature with the E.M.F., is "apparent" power, and is equal to $\frac{\text{K.W.}}{\cos \phi}$.

From the operating aspect, the importance of the attainment of low-power factor lies firstly in minimising dielectric loss *qua* loss, *i.e.* of economy in transmission costs. In a modern 33 K.V. ·2 sq. in. 3-core cable of ordinary construction, the annual charges incurred by dielectric losses will be of the order of 8 per cent. of the total cost of the full load-line losses,* or about 16 per cent. under the more usual conditions of, say, 60 per cent. load factor. It is, however, because the heating due to the loss originates in the dielectric, and therefore tends to " blanket " or to be superposed on the heating due to the copper losses, that the chief limitations arise. Further reference to this will be made later.

* Assuming full load current	225 amps.
„ Temperature at full load	140° F.
„ Conductor resistance at 140° F.	·26ω/mile.
„ Equivalent star capacity at 140° F. . . .	·29 mfds./mile.
„ Power factor at 140° F.	·035.
Under which conditions copper losses will be . . .	40·1 K.W./mile.
„ „ dielectric „ „ „ . . .	3·46 „ „

It has not, perhaps, been sufficiently realised that modern requirements in relation to transmission and distribution by insulated electric cables at pressures of 33 K.V. and upwards, demand an entirely new level of dielectric efficiency, as well as chemical and physical stability.

Seeing that dielectric loss is not only *per se* of primary importance, but also in many ways constitutes a criterion of the fulfilment of these demands, a brief survey of dielectric properties in relation thereto is desirable.

It may here be remarked that few subjects have been so intensively studied and discussed by scientists and engineers; and it is of considerable interest to note the various stages through which our knowledge regarding it has progressed since Faraday,* in 1839, first observed the phenomenon of residual charge.

About a quarter of a century elapsed before further contributions on effects of this nature, encountered in experiments with Leyden jars, were recorded by Werner von Siemens † and some years later by John Hopkinson. ‡

Ayrton and Perry,§ in 1878, discussed conduction in dielectrics, ascribing it to rotary molecular motion (as distinct from motion of translation in conductors), and referred to an observed effect of "strain" under long-continued stress, as dielectric "viscosity."

The chief fundamental work, however, was that embodied in Clerk Maxwell's || classical theories on electric absorption, residual charge, and conduction in stratified dielectrics.

Attempting to briefly summarise these from the cable dielectric point of view, it might be said that if a compound dielectric be supposed, for the sake of simplicity, to be built up of plane strata of different materials (entailing varying electrical properties), and a difference of potential applied in a direction normal to the strata, the fall of potential through the thickness of each stratum will be distributed in proportion to its resistivity and in inverse proportion to its specific inductive capacity. Each will therefore carry different charges, and the equalising current, so to speak, causes the phenomena under consideration.

In modern developments of Maxwell's theory, various investigators, notably Fleming and Dyke,¶ Wagner,** and Del Mar and Hanson,†† have endeavoured to show that if the product of resistivity and specific capacity in two elements, comprising a dielectric, were equal, there would be no residual charge; in which case, presumably,

* M. Faraday, *Experimental Researches in Electricity*, 1839.

† W. von Siemens, "On the Warming of the Glass of a Leyden Jar." *Kön. Preuss. Akademie zu Berlin.* Berichte, p. 614, 1864.

‡ J. Hopkinson, "The Residual Charge of the Leyden Jar." *Phil. Trans.*, vol. 166, p. 489, 1876; and vol. 167, p. 599, 1877.

§ W. E. Ayrton and J. Perry, "On the Viscosity of Dielectrics." *Proc. Royal Soc.*, vol. 27, p. 238, 1878.

|| J. Clerk Maxwell, *A Treatise on Electricity and Magnetism*, 1873.

¶ J. A. Fleming and G. B. Dyke, "On the Power Factor and Conductivity of Dielectrics." *Journ. I.E.E.*, vol. 49, p. 323, 1912.

** K. W. Wagner. *Elektrotech. Zeits.*, vol. 36, p. 111, 1915.

†† W. A. Del Mar and C. F. Hanson, "The Effects of the Composite Structure of Impregnated Paper Insulation on its Electrical Properties." *Journ. A.I.E.E.*, vol. 41, p. 439, 1922.

the energy loss in the whole dielectric would be a minimum. Some degree of experimental support has been adduced by various workers in this direction, but there would appear to be much scope for co-ordinating a better knowledge of chemistry and the ionic theory with electrical research on the subject.

In the early nineties, the " hysteresis " conception of dielectric loss came to the fore, and a flood of discussion followed into the early years of the present century, stimulated by the work of such investigators as Janet,* Arno,† Eisler,‡ Apt and Mauritius,§ Humann,|| and Monasch,¶ on the Continent; Mordey,** Drysdale,†† and others in England; and Steinmetz,‡‡ Skinner,§§ and others in America. Steinmetz appears to have been the first to establish the direct square law relationship between the dielectric loss and the electrostatic strain, thus differentiating its nature from that of magnetic hysteresis (which varies as the 1·6 power of the induction density), and showing its purely ohmic character.

Several contributions were made to the subject during the period 1910-1912, the most important from the power cable point of view being by M. Höchstädter,|||| who reported tests showing that dielectric loss was directly proportional to frequency, and also gave a dielectric hysteresis loop, constructed from oscillographic records, from which in turn he deduced values of residual charge, capacity, and energy loss in the dielectric.

In 1912, Fleming and Dyke's paper (*l.c.*, *ante*) on the power factor and conductivity of dielectrics at telephonic frequencies, gave valuable support to the Maxwell theory. It had little bearing on power cable design, however, except from the theoretical aspect.

K. W. Wagner, in 1913 and also in 1915 (*l.c.*, *ante*), developed Maxwell's theories relating to residual charge and composite dielectrics respectively. He evolved an exponential equation for the former, as did Maxwell, whereas other investigators had suggested a logarithmic law.

In 1917, papers by Clark and Shanklin,¶¶ and R. W. Atkinson,*** were

* P. Janet, "Hysteresis and Viscosity of Mica for Rapid Oscillations." *Comptes Rendus*, vol. 116, p. 373, 1893.

† R. Arno, "Rotating Field and Electrical Hysteresis." *Atti della R. Accademia dei Lincei*, vol. 1, p. 284, 1892; and *Electrician*, vol. 30, p. 516, 1893.

‡ H. Eisler, "Dielectric Hysteresis." *Zeitschrift f r Elektrotechnik*, vol. 13, pp. 345 and 452, 1895; and *Physical Society Abstracts*, vol. 1, No. 594, 1895.

§ R. Apt and C. Mauritius, "Dielectric Hysteresis in High Tension Cables." *Elektrotech. Zeits.*, vol. 24, p. 879, 1903.

|| P. Humann, "Dielectric Losses in Cables." *Elektrische Bahnen*, vol. 4, p. 457, 1906.

¶ B. Monasch, "Energy Losses in Dielectrics." *Ann. Physik*, vol. 22, p. 905, 1907; and *Science Abstracts*, vol. 10, No. 1084, 1907.

** W. M. Mordey, "Power Lost in the Dielectric of Cables." *I.E.E. Journal*, vol. 30, p. 364, 1901.

†† C. V. Drysdale, "Dielectric Losses in Cables and Condensers." *Electrician*, vol. 46, p. 890, 1901.

‡‡ C. P. Steinmetz, "Dielectric Losses." *Elec. Eng.*, vol. 13, p. 272, 1892; *Elec. World*, vol. 37, p. 1065, 1901.

§§ C. E. Skinner, "Energy Loss in Commercial Insulating Materials." *Trans. A.I.E.E.*, vol. 19, p. 1047, 1902.

|||| M. Höchstädter, "Dielectric Losses in High Tension Cables." *Elektrotech. Zeitschrift*, vol. 31, p. 467, 1910.

¶¶ W. S. Clark and G. B. Shanklin, "Insulation Characteristics of High Voltage Cables." *Trans. A.I.E.E.*, vol. 36, p. 447, 1917.

*** R. W. Atkinson, *Trans. A.I.E.E.*, vol. 36, p. 521, 1917.

presented to the American I.E.E. In the former, a large volume of work, covering a wide range of determinations, was apparently marred by the inefficient manufacture of the dielectrics operated upon, which led to severe criticisms of some of the conclusions arrived at.

Atkinson's results, with reference to the variation of loss with frequency, were not so definite as Höchstädter's, above referred to. He only found an approach to direct proportionality in some cases. An interesting and significant result obtained on a dried, but unimpregnated paper cable, was that the loss was very low, and its variation with temperature small.

Höchstädter, in two articles published in 1922,* dealt chiefly with the conclusions of Clark and Shanklin, showing by reference to previous practice that they had laid too much emphasis on ionisation of occluded air and gases as the main cause of failure in impregnated paper cables. It appears to have escaped notice, however, that he confused Clark and Shanklin with Shanklin and Matson, and ascribed to the former statements made by the latter Authors (see p. 239).

Del Mar and Hanson's 1922 *A.I.E.E.* paper, to which reference has already been made under Composition Design (p. 169), was a valuable contribution to the volume of evidence bearing on the Maxwell theory.

As a logical development of Fleming's and Wagner's conceptions, these Authors experimented with two leaky condensers in series, representing a heterogeneous dielectric, having first developed a formula giving the power factor of impregnated paper in terms of the resistivity and specific capacity of the impregnating compound and the paper. The experimental results agreed fairly well with the theoretical figures, and an attempt was made to show a relation between the resistivity of the impregnating compound and the power factor of the impregnated paper dielectric.

It was apparently realised by the Authors that the distribution of the resistances in relation to the capacities in their experimental circuit, in addition to their values, might have a bearing on the agreement between calculated results and values obtained experimentally.

In 1924, Steinmetz,† in characteristically lucid style, presented a mathematical treatment of the Maxwell theory from the aspect of transient phenomena. He considered the application of both direct and alternating voltages, and discussed the distribution of dielectric stress between the components in a dielectric consisting of two or more materials having different resistivities, or different capacities, or both.

A general survey of the foregoing notes can hardly fail to convey the impression that from whatever angle Maxwell's theories have been theoretically examined, they have received general support.

So far as the work of the experimental investigators is concerned, few lines of research have been so hampered by indefiniteness of the materials and combination of materials forming the subject thereof.

The dielectric, for example, on which most of this work has been carried out, viz., impregnated paper, is composed of chemically abstruse components, apart from

* M. Höchstädter, *Elektrotech. Zeitschrift*, vol. 43, 1922.

† C. P. Steinmetz, "Cable Charge and Discharge." *A.I.E.E. Jour.*, p. 525. 1924.

the physical difficulty of definitely combining them, and at the same time excluding other matter such as moisture, air, and gases.

Reverting to the matter of the superposition of heating due to dielectric loss on that due to copper loss, it is well appreciated that the dielectric loss/temperature curve of almost any dielectric material steepens, more or less, towards the higher end of the working temperature range; and in consequence, when the dielectric of a cable becomes heated by the passage of current through the conductor, the above-mentioned superposition may cause a total rate of heating which may become cumulative, and exceed the rate of its dissipation from the cable. Under these conditions, the dielectric rapidly becomes carbonised and breaks down.

The general form of the dielectric loss/temperature curve is as shown in Fig. 38. The characteristic "V" formation applies, in greater or less degree, to practically all makes of impregnated paper dielectric, although it is possible—as shown by recent developments—to flatten out the curve very considerably by modifying the composition and incidentally the physical properties of the impregnating medium.

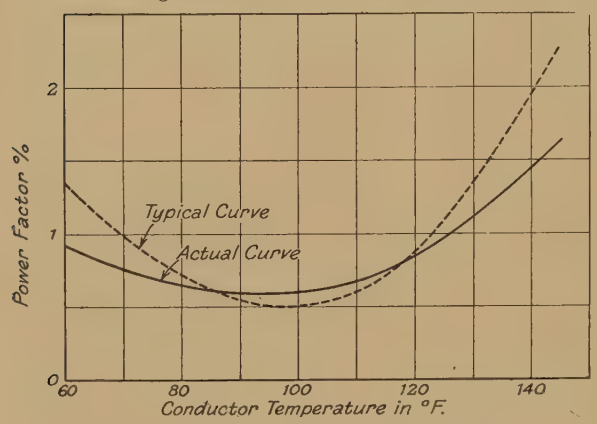

FIG. 38.—VARIATION OF DIELECTRIC POWER FACTOR WITH CONDUCTOR TEMPERATURE.

It is also possible by the same means to lower the minimum point of the curve, although, in the author's experience, the mechanical factor in the case, viz., the building up of the dielectric, has the predominating influence in this direction.

Höchstädter (*l.c.*, *ante*), in 1922, dealt very fully with the causes of this so-called V formation, his conclusion, briefly, being that the minimum portion of the curve represented a transition region closely related to the physical state of the impregnating medium, and that at temperatures below this region the losses were of the character of hysteresis losses, while above they were mainly current losses due to the rapid lowering of insulation resistance with increase of temperature.

In support of this, Höchstädter quoted the work of Pungs * and Wagner,† and gave curves from Pungs relating to the variation of loss with temperature and frequency in a compound of resin and beeswax (which was solid, or at least plastic, at normal temperature) at constant voltage. These curves tended to show that below the softening-point of this compound the loss was proportional to the frequency, and could therefore be presumed to be hysteretic in character; while above, they were independent of the frequency. In view of the rapid decrease of insulation resistance with temperature in such compounds (see Fig. 36, p. 188) there would appear to be strong support for the deduction that ohmic losses predominate at the higher

* *Archiv. für Elektrotechnik*, vol. 1, part 8. † *Ibid.*, vol. 3, parts 3 and 4.

end of the temperature range. With regard to the downward slope of the first part of the curve, Höchstädter explained the decrease of hysteresis loss with temperature as being due to decrease of internal molecular friction with decreasing viscosity of the compound; from previous statements regarding the physical properties of compounds, and references to the experimental results of other investigators earlier in this work, this theory would appear to have some foundation.

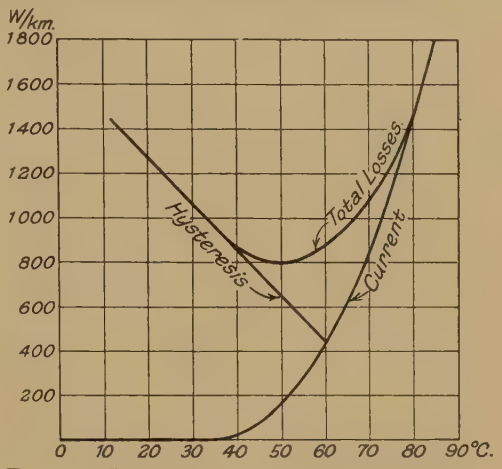

FIG. 39.—CURVE ILLUSTRATING HÖCHSTÄDTER'S THEORY.

Fig. 39, from Höchstädter's article above referred to, illustrates the broad principle of his theory.

Assuming general acceptance of the theory outlined above, it has to be borne in mind that losses due to the ionisation of occluded air and gases in a dielectric, are, like the hysteresis losses, proportional to the frequency, and cannot be separated therefrom by a frequency test.

To avoid complication, ionisation losses have not been considered in the foregoing; they will be referred to in detail later. Their existence and magnitude can be most effectively determined by the loss/voltage curve. Valuable work in this connection has been carried out by Mr C. F. Proos, of the Delft Cable Works, on behalf of the Union of Directors of Electrical Undertakings in Holland, and whose report was submitted in 1923.

Proos not only investigated the loss/voltage and loss/temperature characteristics of certain cables, but also a loss/time effect, which has appreciable importance, not only from the point of view of the behaviour of a cable under working conditions, but also from the testing and standardisation aspects. In fact, methods of testing appear to have given a degree of clarity to his results which has been lacking in those of some other observers. For example, the concise, straight-line form of his watts/E^2 voltage characteristic, reproduced in Fig. 40, can only be attained by a very rapidly performed sequence of tests. (This is another instance of the importance of testing methods, to which reference has been previously made, and possibly has some bearing on discrepancies between the results of different investigators.)

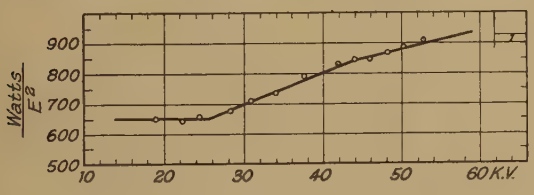

FIG. 40.—VOLTAGE CHARACTERISTIC (PROOS).

It will be seen that the voltage characteristic consists of three parts, firstly a horizontal portion, in which the losses are proportional to the square of the voltage; next, a steeply rising part, in which the point of departure from the square law undoubtedly indicates the commencement of ionisation of occluded air and gases; and

finally, a less steep part, which is taken to represent a condition in the dielectric when the "free" air—which probably means films of the larger order of thickness —has been more or less completely ionised. The first point of departure from the quadratic law is obviously the more important, and the variation in the voltage value at which it occurs in three 10-K.V. cables of similar type and size, due to differences in the process of manufacture, are exemplified by the Author (14, 20, and 23 K.V. respectively).

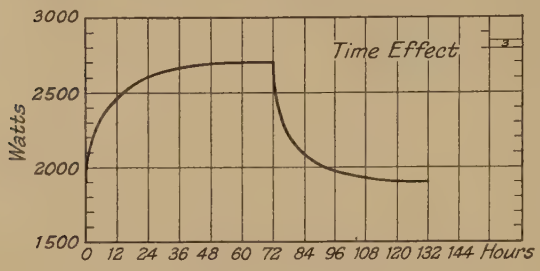

Fig. 41.—Time Effect (Proos).

The time-effect above referred to is illustrated in Fig. 41, taken from Proos' Paper. The tests represented therein were taken on a 300-metre length of single-core 95-mm. cable insulated with 8·5 mm. of paper, laid in the ground. A pressure of 40 K.V. was continuously applied, lowered to 30 K.V. from time to time for the purpose of taking the loss measurements. When no further increase in loss with

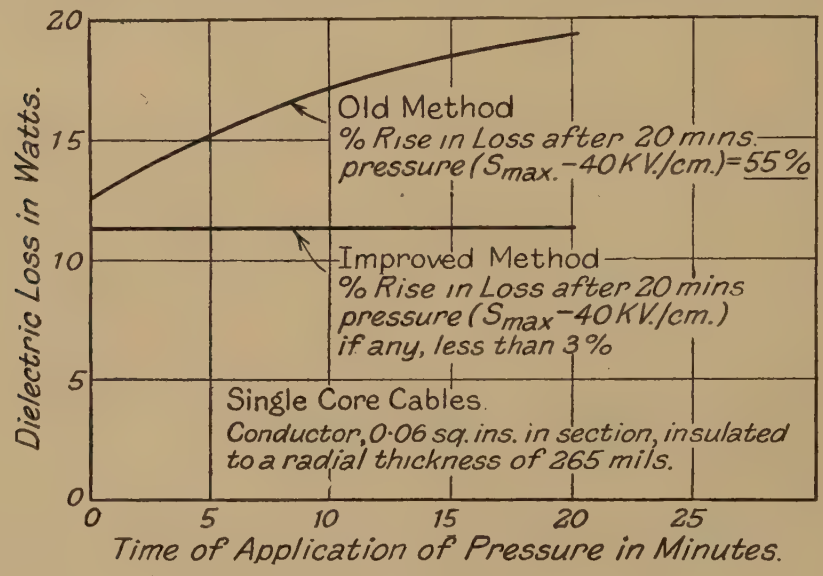
Dielectric Loss in Watts.
20
15
10
5
0
Old Method
% Rise in Loss after 20 mins. pressure (Smax.-40 KV./cm.)=55%
Improved Method
% Rise in Loss after 20 mins pressure (Smax-40 KV./cm.) if any, less than 3%
Single Core Cables.
Conductor, 0·06 sq. ins. in section, insulated to a radial thickness of 265 mils.
0 5 10 15 20 25
Time of Application of Pressure in Minutes.

Fig. 42.—Example of Comparative Loss/Time Test.

time was found, the cable was disconnected and loss measurements taken at regular intervals. The curve shows the gradual return to normal loss value.

The Author carefully distinguishes this time-effect from any effect due to temperature rise in the dielectric. He proceeds to show its result on the second (ionisation of "free" air) part of the voltage characteristic, and on the apparent ionisation point, which becomes slightly reduced under prolonged time conditions, *i.e.* when the tests are not taken with sufficient rapidity.

The present writer has utilised this time-effect as an independent test for the comparison of dielectrics. Fig. 42 shews an example of such a comparison which relates to an improved manufacturing method described later in Vol. II. The time is restricted to twenty minutes in order to minimise temperature effects.

The actual effect of ionisation of occluded air and gases in an impregnated paper dielectric, short of actual burning effects, is rather obscure. Many cases have been reported, in which " tree-like " carbonised patterns on the paper surfaces, and a transformation of the impregnating compound from its originally oily state into a waxy or " cheese-like " consistency have been observed. In the author's experience these appearances only occur in cases of actual or incipient breakdown. On the other hand, there are a very large number of cables at work in all parts of the world under conditions of temperature and electric stress appreciably exceeding those at which ionisation of air and gases, which are certainly occluded in them, must occur in the course of their daily duty (see p. 243).

With regard to the physical, mechanical, and chemical properties of dielectrics *qua* dielectrics, preceding sections of this work, *e.g.*, dealing with materials, mechanical principles of design, composition design of dielectrics, etc., will have conveyed general ideas on this part of the subject.

Owing to their wide divergence in the different types of dielectric, the difficulty of assigning " specific " values to these properties is perhaps even greater than in the case of electrical properties.

They can only be defined with relation to results produced on specified forms, volumes, or masses by the application of certain stresses, or by exposure to inimical effects. In the absence of standardised methods and conditions of determination, and of units appropriate to the requirements, both criteria and results have to be expressed in somewhat arbitrary terms.

As our purpose at the present juncture is simply to consider the above-mentioned properties of dielectrics from the aspect of suitability on the one hand, and limitations on the other, of the various types under the exigencies of working conditions, the major portion of the available information regarding such properties will be more appropriately dealt with under the heading " Testing " (Materials), in Volume II.

PHYSICAL PROPERTIES

Coyle and Howe (*l.c.*, *ante*) give the following approximate values for the specific gravities of paper, rubber, and bitumen dielectrics :—

Raw Paper . .	0·8 to 0·85	Rubber (Pure) .	0·935 to 1·0
Impregnated Paper	1·10	Rubber (Vulcanised) *	1·3 to 1·7
Impregnated Jute .	0·875	Vulcanised Bitumen	1·2 to 1·3

It has already been pointed out (p. 169) that values of specific gravity have little direct bearing on design from the scientific aspect, except that variations in

* See Fig. 43.

electrical values in certain materials closely correspond with changes in their physical state due to temperature, which in turn affects their specific gravity.

The figures in the above list are probably intended by the authority quoted to simply represent average values for use in computing weights of material. Except perhaps in the case of pure rubber (Para being understood) the specific values will vary according to conditions and methods of manufacture or according to composition; for example, in paper according to the length and "felting" of the fibres and treatment (*e.g.*, degree of calendering) affecting the density and incidentally the absorbency of the sheet; in vulcanised bitumen according to the mineral content; * and in vulcanised rubber according to certain physical properties (other than specific gravity) of the mineral ingredients. In the latter connection, the author does not agree with Caspari † that the specific gravity of a rubber compound may be calculated from the specific gravities of its components, and a brief note on this point may here be of interest.

It is common knowledge that certain mineral powders used in rubber compounds are much more easily mixed with or taken up by the rubber than others. For example, zinc oxide is much more readily absorbed in the mixing operation than, say, whiting. This is not entirely a matter of fineness of division of the particles, but probably partakes more of the nature of such a property as surface tension.

The result of this is to cause variations from the simple proportionality of the S.G. of the components to that of the compound. To take a simple concrete example, if, in a 30 per cent. rubber compound, containing among other ingredients (of the class referred to on p. 90 *et seq.*) 20 per cent. zinc oxide and 16 per cent. of whiting, a portion of these two ingredients is transposed, making their proportions 16 per cent. and 20 per cent. respectively, the S.G. of the compound will be found to be decreased by about 9·5 per cent. Again, if 4 per cent. of the whiting in the first-mentioned compound is replaced by a similar percentage of litharge, the S.G. is not increased.

The general order of variation in a given range of rubber compounds, in which the same mineral ingredients are employed in approximately constant ratio to each other, is as shown in Fig. 43. It may be noted that the same *order* of variation applies to vulcanised bitumen compounds.

With regard to the thermal constants of dielectrics, heat conductivity is of chief practical concern. Emissivity does not usually come into consideration, as dielectrics are seldom exposed directly to the atmosphere.

Table XIV shews a few values of thermal conductivity determined by the author in the research laboratories of Messrs W. T. Glover & Co., Ltd., on

* The specific gravity varies in different makes from 1·076 to 1·31. *Vide* Atkinson and Beaver, "Some Points on the Selection of Electric Cables" (*l.c.*, *ante*).

† *India Rubber Laboratory Practice*, p. 107. Caspari says: "The specific gravity of vulcanised rubber goods containing auxiliary materials, as determined by hydrostatic weighing, may be calculated additively from the components, assuming always that there are no vacuoles in the rubber. A quality made up of *a* parts of vulcanised rubber, sp. gr. A, *b* parts of a filler, sp. gr. B, *c* of another filler, sp. gr. C, and so on, will have the specific gravity—

$$\frac{a+b+c+\ldots}{\frac{a}{A}+\frac{b}{B}+\frac{c}{C}+\ldots}$$

dielectric materials used for cable insulating purposes, and some component materials, such as impregnating compounds.

A few values published by other observers are included for the sake of comparison. Some of the earlier investigators give their results in calorie measure, and the more recent ones in thermal ohms, *i.e.* in terms of the difference in temperature in degrees Centigrade which would be necessary to cause a flow of heat per second equivalent to one joule between the faces of a centimetre cube of the material. These have been converted for the purpose of the Table into the more explicit watt measure. (1 watt = ·24 gram-calorie per second.)

In the Table, thermal conductivity, k, represents watts per cu. cm. (or per sq.

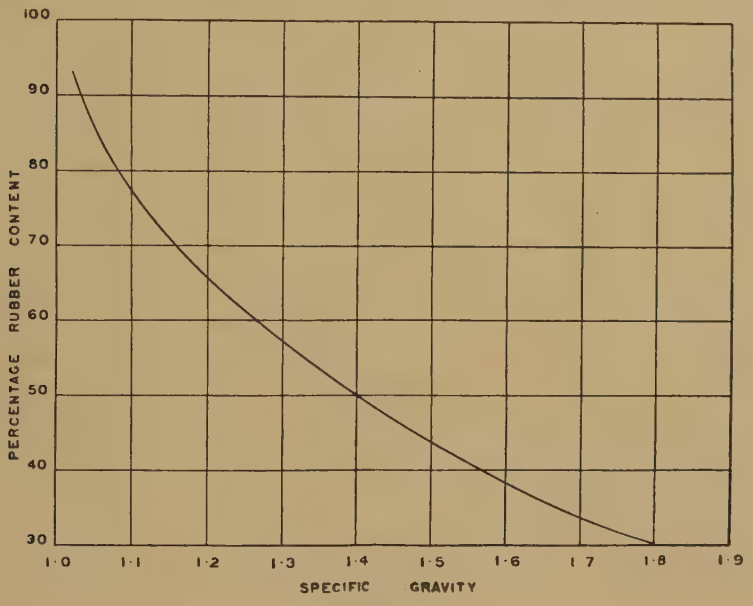

Fig. 43.

cm. per cm. length of path), per ° C., while thermal resistivity K is, of course, the reciprocal of thermal conductivity in the same measure.

The reason for showing both in the Table is that, while students of physical science are more accustomed to consider thermal characteristics of materials in terms of heat conductivity, cable makers and users have in recent years become familiarised with the thermal resistivity conception and the general order of figures expressed in this form for insulating materials, largely on account of its adoption in the B.E.A.I.R.A. Reports on the Heating of Buried Cables.

In their Second Report on the Heating of Buried Cables (*ibid.*), Melsom and others adopted different values of K for cables for pressures up to and including 2200 volts, and for those for pressures above 2200 volts up to and including 11,000 volts, viz., 750 and 550 respectively. Teichmuller and Humann (see Table XIV) also differentiated between low-tension single, low-tension multicore, and high-tension

TABLE XIV

Material.	Observer.	k= Thermal Conductivity.	K= Thermal Resistivity.	Remarks.
Diatrine Impregd. Manilla Paper	Author	0·00173	578	Determined in special apparatus. The difference between the two values represents the result of variations in paper lapping, the second being specially tightly lapped.
" " " "	"	0·00182	550	
Impregd. Paper (composition unrecorded)	Matsumoto *	0·00160	623	Determined on cables.
" " "	Melsom and Booth †	0·00112–0·00134	980–748	Determined on cables, stated to vary with size of cable and current density.
" " "	Atkinson and Fisher ‡	0·00100–0·00115	1000–870	Determined on cables.
" " "	Teichmuller and Humann §	0·00154–0·00182	650–550	The higher value of "K" stated to apply to single L.T., and the lower to multicore H.T. cables.
" " "	Powell ‖	0·00081–0·00114	1235–877	Determined on cables.
" " "	Apt and Mauritius ¶	0·00149–0·00279	678–359	Determined on cables.
"Rope" Paper and Oil	Langmuir **	0·00140	714	"Rope" Paper is an American term, intended to indicate that the raw material from which the paper is made is (Manilla) rope.
" " "	Symons and Walker ††	0·00142	704	Determined in special apparatus of somewhat similar character to that constructed and used by the author.
"Rope" Paper (treated with varnish)	" "	0·00170	589	
" " "	Langmuir	0·00170	589	
"Rope" Paper (untreated)	"	0·00120	834	
" " "	Symons and Walker	0·00115	870	
Manilla Paper (untreated)	Author	0·00085	1188	Determined in special apparatus.
Paper (composition unrecorded)	Porter ‡‡	0·00129	776	No reference to composition or physical details.
" " "	Melsom and Others §§	0·00104	960	
"Diatrine" impregnating compound	Author	0·00150	668	Referred to on p. 170, Fig. 31, Curve A.
60 % Resin, 40 % Resin Oil	"	0·00180	556	Made with F grade resin and refined commercial resin oil, free from resin (see Figs. 31 and 45).
20 % Resin, 80 % "	"	0·00301	333	

45 % Bitumen, 55 % Min. Oil	,,	0·00195	513	Natural bitumen of the Mexican type, compounded with pure mineral oil of specific gravity 0·9 at 70° F., viscosity 96 at 70° F., and flash-point (closed test) 415° F.
Petroleum Jelly	,,	0·00217	461	Referred to on p. 170, Curve D of Fig. 31.
Pure Rubber	,,	0·00150	668	Pure unvulcanised sheet as used for the production of pure rubber strip.
"Para" Rubber	Porter	0·00158	632	Form and quality unrecorded.
,, ,,	Langmuir	0·00160	623	Presumably pure rubber.
Vulcd. Rubber Compounds—	Author			
(*a*) 30 % Rubber Content		0·00310	322	Rubber compounds of the class previously referred to as being used for cable dielectrics. See pp. 176 *et seq.*
(*b*) 48 % ,,		0·00218	465	
(*c*) 70 % ,,		0·00194	515	
Vulcanised Bitumen	Marchant §§	0·00196	510	Determined on cables.
,, ,,	Melsom and Others	0·00206	486	Material only.
,, ,,	Author	0·00210	475	Determined in special apparatus.
Varnished Cambric	Langmuir	0·00250	400	Materials not described in detail.
,, ,,	Symons and Walker	0·00249	402	Symons and Walker refer to theirs as "Empire Cloth."
,, ,,	Dushman ||||	0·001–0·0013	1000–770	
,, ,, (dry)	Author	0·00241	415	Good average material of British manufacture. Count 100×100. Thickness of sheets, 6 mils. Thickness of wall in test samples varied from 250 to 312 mils. Compound between layers (called "slipper" compound in America) was Petroleum Jelly.
,, ,, (compound between layers	,,	0·00233	429	

* Report No. 24 of Electro-Technical Laboratory, Tokio, 1916.
† "The Heating of Cables with Current," *Journal I.E.E.*, 1911, vol. 47, p. 711.
‡ "Current Rating of Electric Cables," *ibid.*, 1913, vol. 32, p. 325.
§ "Heating of Cables," *Elekt Zeits.*, 1906, vol. 27, p. 579; Article on "Experiments on the Heating of Underground Cables," *ibid.*, p. 813.
‖ "Temperature Rise of Insulated Lead-covered Cables," *ibid.*, 1916, vol. 35, p. 1017.
¶ "Heating of Underground Three-phase Cables," *ibid.*, p. 1008; Letter to Editor, *ibid.*, 1905, vol. 26, p. 207.
** "Heat Transmission," *JournalA.I.E.E.*, vol. 32 (1), 1913.
†† "The Heat Paths of Electrical Machinery," *Journal I.E.E.*, 1912, xlviii.
‡‡ "On the Lagging of Pipes and Wires," *Phil. Mag.*, 1910, xx.
§§ Report "On the Research on the Heating of Buried Cables," *Journal I.E.E.*, 1923, vol. 61, p. 517.
|||| "The Heating of Cables Carrying Current." *Journal A.I.E.E.*, vol. 32, p. 333, 1913.

multicore cables in this respect. There is no sound technical reason for this, as it might be fairly expected that the smaller number of paper layers and the greater ease of impregnation in the case of the low-tension cables, would result in a more —not less—homogeneous dielectric, with a lower, rather than a higher thermal resistivity.

The figures recorded in Table XIV show fair agreement between various observers, and a general survey tends to show, firstly, a certain degree of distinction between the order of values for each type of dielectric ; and secondly, the effect of components on the values for the complete material, which is well illustrated in the cases of impregnated paper and vulcanised rubber.

With regard to the former point, however, it must be borne in mind that the

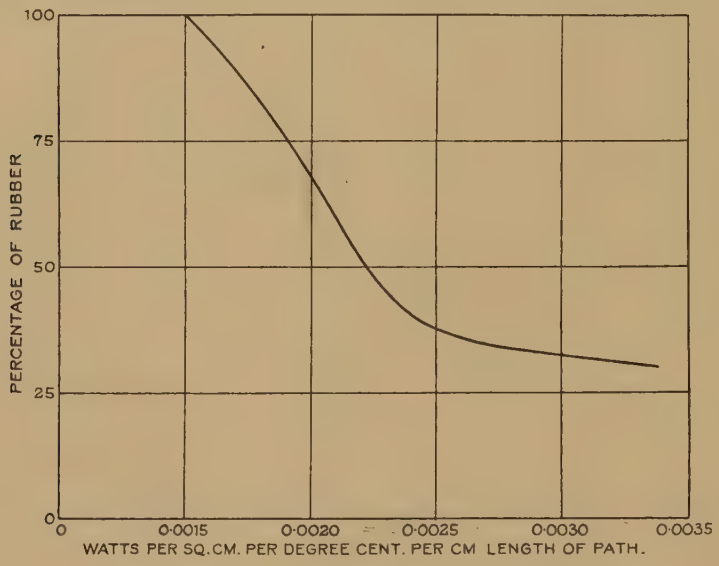

Fig. 44.—Thermal Conductivity of Vulcanised Rubber.

values relate to dielectric materials only, and that the apparent advantage which a 50 per cent. rubber compound (or vulcanised bitumen) may have over impregnated paper from the thermal conductivity aspect, may be nullified by the difference between the thermal properties of the sheaths, coverings, etc., which may be respectively applied over them. Consequently, while good agreement is observed between values for impregnated paper in the form of made-up test samples, and as determined on lead-sheathed cables, a considerable difference is entailed in the case of rubber or vulcanised bitumen, having the more usual braided or taped coverings over the dielectric.

While the thermal resistivity of lead is 2·9, that of a compounded tape or braid is of the order of 520 to 540.

Fig. 44, representing a series of determinations from which the values given in the Table have been abstracted, shows, *inter alia* (by reason of the distortion at the

upper end of the curve), the effect of vulcanisation on thermal conductivity, the uppermost point on the curve representing pure unvulcanised rubber.

Referring to the effect of components in the case of impregnated paper, the author's experiments incidentally threw light on the question as to whether the thermal resistivity of insulating materials has a temperature coefficient. They clearly showed a decrease in resistivity with increasing temperature in all cases where the material underwent physical change (decrease in viscosity), under the mean temperature conditions employed, which usually ranged in each series of determinations from 32° to 65° C. It will be apparent from the list of materials given in the Table that only impregnating compounds would fall into this category, although, as might be expected, there was a slight indication in the case of

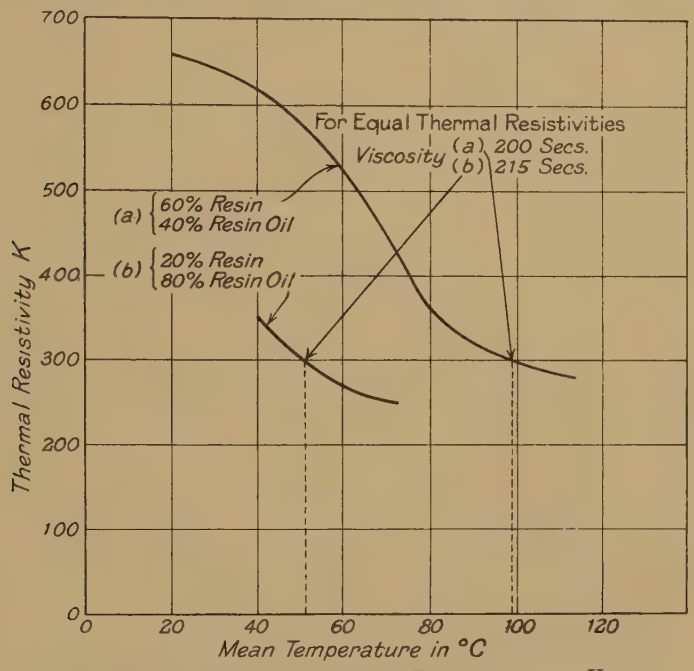

Fig. 45.—Relation between Thermal Resistivity and Viscosity.

impregnated paper.* There was no sign of such variation unaccompanied by change in physical consistency, even in materials liquefiable by heat, such as Trinidad bitumen; although, as this material possesses viscosity, the effect might have been traceable at higher temperatures than those employed.

This relation between thermal resistivity and viscosity was particularly noticeable in the 60 per cent. resin/40 per cent. resin oil compound, and appeared to indicate the reason for the wide difference between the average value obtained from it and that shown by the less viscous 20 per cent. resin/80 per cent. resin oil compound.

Experiments at equal viscosities shewed approximately that this was the case,

* Melsom, in his experiments on cables, could not trace this.

as illustrated by the curves in Fig. 45; and we therefore have at least a general indication that with regard to thermal resistivity, temperature and viscosity (in substances which possess this property) may be more or less convertible terms.

The possession of a negative temperature coefficient of both thermal and electrical resistivity by viscous non-conducting materials, compared with the positive coefficients in both properties possessed by most conducting materials,* has a significance which would appear to be particularly worthy of note, especially in view of other relationships between physical, chemical, and electrical properties already noted. For example, it would be of interest to link up the property of dielectric strength to that of thermal (and consequently electrical) resistivity on the lines of the work of Del Mar and Hanson (*l.c.*, *ante*, p. 169), which, in effect, tended to show a relation to viscosity or its equivalent, *i.e.* by impeding—or facilitating—ionic travel in oil.

One of the most important physical points in connection with dielectrics relates to hygroscopicity.

It may be taken as axiomatic that all fibrous insulating materials are—and for cable dielectric purposes must be rigidly considered as—hygroscopic, even when thoroughly impregnated with compound, coated with varnish, or treated by any other commercially practicable method.

In this connection it is common practice to apply a waterproof sheath to impregnated paper cables, and to definitely protect ends, joints, and all parts where the dielectric may be exposed, from atmospheric moisture. The degree of "hygroscopic susceptibility" of varnished cambric is considerably less than that of impregnated paper, because the fibrous material is—more or less perfectly—enclosed between films of varnish; but, as previously pointed out,† it is necessary to provide it with similar protection, because its advantages in this direction are more or less a matter of degree.

The primary effect of absorption of moisture is chiefly physical, and only to a limited extent produces chemical change in fibrous dielectrics, although a slight hydrolytic action on resinous impregnating media or oil-varnished coatings may superficially occur. Some slight degree of hydration of the cellulose may occur in the case of an impregnated paper dielectric under advanced temperature conditions, although direct proof of this is difficult because of the secondary effects which supervene when sufficient moisture has been absorbed to permit the passage of leakage current through or along the moistened path. In this event electrolytic effects will occur which may cause metallic salts or even deposits of metal to be formed on or in the fibrous mass, as described under "Deterioration," Volume II.

For practical purposes vulcanised rubber and vulcanised bitumen may be considered as non-hygroscopic, although, from what has preceded on the subject of dielectric design, it will be realised that molecular structure has some influence in determining the actual degree of resistance to water, and that a continuous metallic sheath constitutes the only perfectly effective barrier to water, especially under conditions entailing appreciable hydrostatic pressure.

It may be mentioned in passing, in view of common misapprehensions on the point, that pure (unvulcanised) rubber is hygroscopic to a very considerable extent.

* Tait, *Trans. R.S.E.*, 18th March 1878.

† Chap. I., p. 26.

MECHANICAL PROPERTIES

The absence of elasticity in fibrous dielectrics, referred to under Mechanical Principles of Design, p. 136, together with the fact that, as mentioned above, their hygroscopicity necessitates the provision of a waterproof sheath (usually metallic), puts them out of consideration where such mechanical properties as flexibility—in the sense of portability—are desired.

Of the non-fibrous dielectrics, rubber is much more suitable in this direction than vulcanised bitumen, on account of its superior strength and resilience. In the case of flexible multicore cables, however, in which the cores are insulated with rubber, vulcanised bitumen is of considerable use as a waterproof sheath, especially when the sheath is internally ribbed to fit the cores (as described on p. 255), thereby obviating the use of fibrous padding; also, in cases where the required degree of flexibility permits the use of varnished cambric insulated cores, *i.e.* where portability only amounts to occasional removability. Vulcanised bitumen sheaths, however, need further mechanical protection, whereas tough rubber sheaths (more usually employed nowadays in the case of flexible rubber cables) seldom need reinforcement.

With regard to resistance to blows, crushing, local mechanical pressure, acute bending, etc., resulting in bursting, tensile, or tearing stresses in the superposed strips of fibrous dielectric materials, varnished cambric has some advantage over paper; but as in cables having fibrous insulation, considerable damage to the lead sheath must occur before such stresses can harm the dielectric, and as the integrity of the lead sheath is of fundamental importance—its primary function being to exclude moisture—such advantage is of no practical moment. Of the waterproof types of dielectric, from this mechanical aspect, rubber is inherently better than vulcanised bitumen, and for this general reason the radial thicknesses employed with the latter material are always greater than for rubber; moreover, vulcanised bitumen is not used for wiring work, etc., in which sharp bends entailing local mechanical pressure frequently occur. Under conditions of use, however, where blows or crushing stresses are liable to occur, both rubber and vulcanised bitumen are usually armoured so that the choice between them turns on questions of cost and durability.

CHEMICAL PROPERTIES

The latter is essentially a matter of chemical stability. Comparisons in this respect are somewhat difficult because the susceptibility to chemical change depends, in various peculiar ways, more on extraneous conditions than on the normal inertness or stability of the dielectric materials themselves. For example, vulcanised bitumen is in itself a singularly stable compound under normally sound conditions of working, being practically free from the natural deterioration (with time) common to all kinds of vulcanised rubber.* It is, however, more susceptible to effects set up by electrically

* Maxwell and Monkhouse (*l.c.*, *ante*) also point out that it "has the appearance and general characteristics of rubber, and yet is absolutely unaffected by continued exposure to hot transformer oil."

unsound conditions which may operate, as pointed out by the author in his Paper on " Cables " (*l.c.*, *ante*), in two distinct ways :—

(*a*) by the direct but localised action on the vulcanised bitumen of strongly alkaline substances formed as a result of the passage of leakage current at faults in a negative cable, and

(*b*) by a more general action, of hydrolytic character, which may be set up on the exterior surface of an electrically sound dielectric under certain conditions of temperature and moisture, facilitated by a somewhat obscure, but well-marked effect of extraneous leakage current, which is independent of polarity, or whether the current is direct or alternating.

Apart from the effects of such electrically unsound conditions, however, the chemical stability of vulcanised bitumen under conditions of normal atmospheric moisture and temperature is generally greater than that of vulcanised rubber ; so that if by maintenance precautions electrically sound conditions are ensured, the superior chemical stability of vulcanised bitumen would, in view of its lower cost, render it in many cases—technically and commercially—a more efficient dielectric, in spite of the mechanical necessity for greater radial thicknesses to be used.

With regard to the chemical stability of the fibrous dielectrics, seeing that for hygroscopicity reasons they are sheathed with lead or vulcanised bitumen, deterioration due to moisture and atmospheric conditions does not enter into the question. Confining our attention to paper as the material of chief importance in this connection, and assuming the absence of self-deteriorating agencies, such as residual chemicals, only temperature effects remain to be considered.

In the case of a low-tension cable, these are simply dependent on the I^2R losses in the conductor, the initial temperature of the cable, and the thermal resistivity of its surroundings ; but in the high-tension case, we have—superposed on this—heating due to dielectric losses, which, as shown in Fig. 38, p. 194, increase with temperature. The cumulative heating which may occur in the latter case, to which reference has already been made, may proceed rapidly to the decomposition point of the dielectric or of some of its components, whereupon breakdown ensues. In the low-tension case, cumulative effects are absent (except for the comparatively negligible increment due to the temperature coefficient of the conductor), and consequently two points of difference arise in the result due to the rate of heating. Firstly, the apparent decomposition points are (palpably, though not demonstrably) different ; and secondly, in the high-tension case, the decomposition is localised around the point or points of failure, whereas in the low-tension case it is general.

With regard to these differences, it must be borne in mind that fibrous materials have no definite decomposition point, although, as is well known, there are critical temperatures—or a critical range of temperature—for various forms of cellulose, above which they deteriorate rapidly. It is not so generally appreciated that slow decomposition occurs well below such critical values, at rates which vary with the conditions of exposure. Little definite data is available, however, which takes into

account the vital factors of chemical composition, physical structure, and manufacturing history of the material.

Prof. Elihu Thomson,* many years ago, stated that in the course of prolonged heat tests on cotton-covered wire, he found that a gradual deterioration of the cotton was evident at 100° C., and that " at any point above 100° C. it was pretty rapid."

In 1916, L. Schuler,† in a report submitted by the Testing Bureau of the German Government, stated that under given conditions of prolonged heating the mechanical strength of cotton and cable paper, after a period of fall, tends to reach a steady value depending on the temperature. On the assumption that it would be safe to

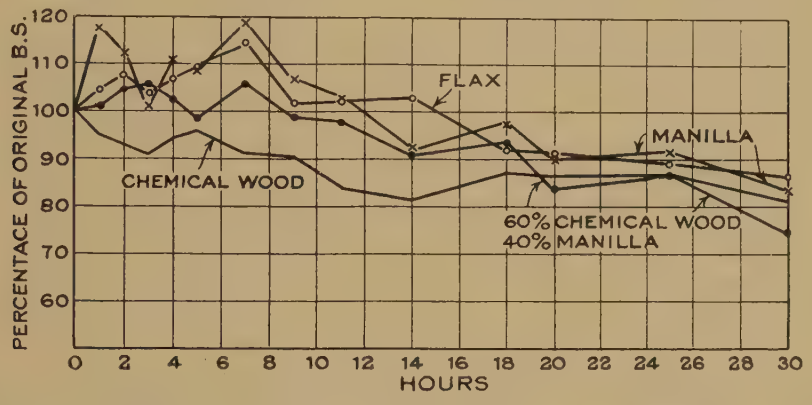

Fig. 46.—Percentage of Original Breaking Strain of Paper immersed in Oil at 270° F. (132° C.).

allow this lower steady value to be 40 per cent. of the initial value, Schuler deduced from his curves the following permissible temperatures :—

Cotton in air	102° C.
,, ,, oil	114° C.
Cable paper in oil	125° C.

Maxwell and Monkhouse (*l.c., ante*) gave results of experiments showing the deterioration of five papers of different composition with increasing temperature in terms of breakdown voltage on samples tested in oil. No reference to the time of exposure to the various temperatures was made, but a diminution in puncture voltages of from 5·1 per cent. in a cotton paper, to 25·7 per cent. in one described as Manilla, was noted at 40° C. (104° F.), as compared with the original values at 20° C. (68° F.), indicating that some degree of decomposition had taken place, even at that low temperature.

Some comparatively recent results obtained by the author are illustrated in Figs. 46, 47, and 48. They are based on temperature and time conditions which have been chosen to represent " ageing " tests, the criteria being mechanical, and —in the case of the samples heated in oil—electrical breakdown tests. The materials

* *Trans. A.I.E.E.*, vol. 14, p. 265, 1897.

† *Elekt. Zeits.*, pp. 535-7, 5th Oct. 1916, and *Science Abstracts*, Section B, No. 230, p. 51.

may be taken to represent good average cable papers of their respective kinds, of modern and reputable manufacture. Points on the curves represent at least five or six tests on samples withdrawn at the times indicated.

The broad similarity between mechanical and electrical deterioration in the oil-

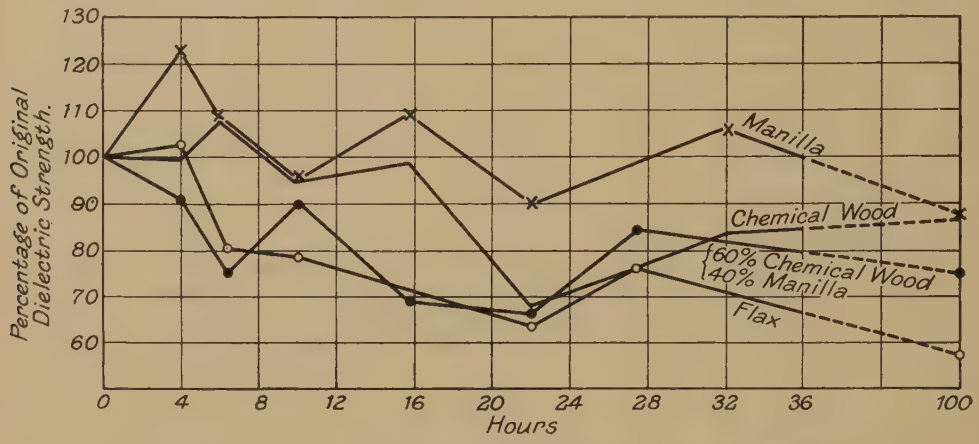

FIG. 47.—PERCENTAGE OF ORIGINAL DIELECTRIC STRENGTH OF PAPER IMMERSED IN OIL AT 270° F. (132° C.).

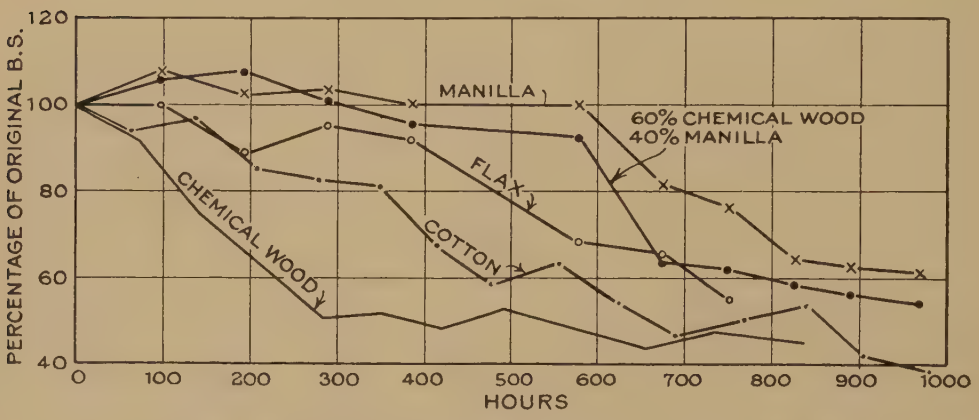

FIG. 48.—PERCENTAGE OF ORIGINAL BREAKING STRAIN OF PAPER SUBMITTED TO A TEMPERATURE OF 250° F. (121° C.) IN VACUO.

immersed samples is interesting, and the general order of merit as regards fibrous composition is noteworthy. In the latter respect there is a similarity between these results and some which were given by Ll. B. Atkinson and the author in 1905 (*l.c.*, *ante*).

It should here be remarked that some degree of caution should be exercised in drawing conclusions from these or similar results obtained from such materials, because such factors as physical structure of the paper and its manufacturing history loom large in the whole perspective of the subject. It is practically impossible to index such a fundamental factor as manufacturing detail beyond stating, for example, that

the papers referred to in Figs. 46, 47 and 48 are pure unsized, unglazed papers made for cable-insulating purposes. Again, no standard is available for the description of structure, which is related to the degree of fineness to which the fibres have been beaten, and in turn, to possible hydration of the cellulose producible by the beating operation; which, again, may have an effect on the results.

With these points in mind, it is not surprising that such data as has been published may appear to be conflicting, though it might not actually be so if all details were definitely taken into account.

Passing from the chemical aspect which relates to the intrinsic chemical stability of the fibrous material, to one which bears on conditions which may be set up during the working life of the cable, it will be evident from the viscosity curves of typical impregnating compounds (Fig. 31, page 170) that there will be a tendency in some cases for them to drain away from the interstices between surfaces of paper or varnished cambric at elevated temperatures, leaving cavities, the air in which may be converted into ozone by ionisation, if the electric stress across them is sufficiently high.

The purely chemical effect of this on the usual types of impregnated paper is not always very marked, although in some cases pronounced effects have been found (see p. 197). On the coating of varnished cambric, however, it readily produces a superoxidising effect, which not only breaks down the flexible structure of the varnish film, but changes it into a strongly acid body.* This in turn acts upon the fabric, and also upon the conductor and sheathing metal with which it may be in contact, causing rapid failure.

Ozone is also produced by " brush discharge " at the ends of high-pressure cables, and if the terminal sealing which is imperative in the case of paper insulation is not applied to varnished cambric dielectrics, similar chemical deterioration may occur to that mentioned above.

In passing, a curious fact may be noted in connection with the action of ozone on rubber, which has in the past given a considerable amount of trouble at terminal ends, viz., that the peculiar splitting phenomenon which is usually observed, and which is the primary cause of the said trouble, and not an effect, takes place very readily when the cable end is in a bent position, *i.e.* when part of its circumference is subjected to tension. The author has experimentally shewn † that this phenomenon takes place in a sample of rubber insulation within the space of a few minutes in a current of ozone when the sample is bent, the splitting being confined to the part of the tube under the tensile stress consequent on the bending. The same material, not subjected at any part of its length or circumference to tensile stress, is unaffected.‡

* Beaver, Discussion on Fleming and Johnson's Paper on " Chemical Action in the Windings of High Voltage Machines," *Journal I.E.E.*, vol. 47, 1911.

† Beaver, Insulated Electric Cables, Glazebrook's " Dictionary of Applied Physics," vol. 2, p. 100, 1923.

‡ Since writing the above, the author has noticed a reference to the phenomenon by Mr W. Thomson in the *Journal of the Society of Chemical Industry*, No. 8, vol. xxxvi. Mr Thomson said: " A curious oxidising effect he had observed was that by passing ozone over a piece of stretched rubber thread, the stretched thread was destroyed within a few minutes, whilst the unstretched part was apparently uninjured."

It may further be of interest to note the fact demonstrated by other experiments carried out by the author on the subject, that while vulcanised bitumen is immune from this action, the admixture of more than 10 per cent. of rubber in the vulcanised bitumen cancels this immunity. Reference is made elsewhere in this work * to the use of vulcanised bitumen as an " ozone-proof " covering for rubber dielectrics of high-pressure cables.

The ultimate practical limitations of each type of dielectric will clearly depend on their electrical, physical, mechanical, and chemical properties as summarised above, and the choice of type for a given duty should be based thereon.

As has been generally indicated, combinations of the dielectric materials may be employed in order that one may supplement the deficiencies of another to the greatest degree of technical and commercial efficiency.

Perhaps the best illustration of this would be to take a broad survey of the manner in which present-day practice distributes the different types of dielectric in various fields of usefulness.

The following list will perhaps be sufficiently comprehensive for this illustrative purpose, although it will be borne in mind that methods of laying and installation will always have a bearing on the matter of selection in detail.

General Purpose	*Type of Dielectric*
High pressure transmission feeders.	Impregnated paper.
Low pressure distribution network.	Impregnated paper, vulcanised bitumen.
Power distribution in large and scattered works.	,, ,, ,, ,,
Internal cabling in power and sub-stations, factories, mills, warehouses, etc.	Paper, vulcanised bitumen, vulcanised rubber, varnished cambric.
Power transmission in mine shafts and workings.	Vulcanised bitumen, paper. Occasionally varnished cambric, vulcanised bitumen sheathed.
Portable purposes, such as trailing cables for coal-cutters, travelling cranes, portable tools, lifting magnets, etc.	Vulcanised rubber.
Semi-portable purposes, such as for sinking pumps, swing bridges, dock-gates, dredgers, etc.	Vulcanised rubber, vulcanised bitumen or vulcanised rubber sheathed; or varnished cambric, vulcanised bitumen sheathed.
Small internal wiring.	Vulcanised rubber.

It will be understood with regard to the above list that :

(*a*) Impregnated paper is metal-sheathed.

* Vol. II.

(*b*) Vulcanised bitumen includes the paper-insulated, vulcanised bitumen sheathed (paper leadless type).

(*c*) Vulcanised rubber—apart from sheaths—is pure and V.I.R.

(*d*) That special compounds, such as Gloverite, Maconite and others referred to on page 21, may be used in substitution for either vulcanised rubber or vulcanised bitumen in special cases for which they are suitable.

CHAPTER X

FACTORS IN VOLTAGE RATING

POTENTIAL GRADIENT

It is well known that the distribution of stress in an electrically homogeneous dielectric surrounding a cylindrical conductor (as, for example, in a single-core metal-sheathed cable) is not, as in the case of a slab lying between flat plates, of uniform character; it is at a maximum at the inner surface, decreasing to a minimum at the outer boundary according to an inverse law with respect to the radius of the point under consideration.

Concentric circles in such an annular form of dielectric represent equipotential surfaces; and the electric stress thereat, when a difference of potential is set up between inner and outer surfaces, is commonly called the potential gradient, or electric field intensity, expressible as a differential dv/dr, where r is the radius of the equipotential surface, and v its potential.

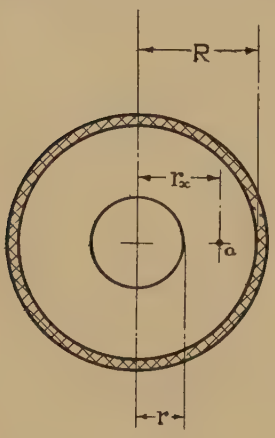

Fig. 49.

So far as the author is aware, Swinburne * was the first to emphasise the application of Clerk Maxwell's theories to the slope of potential in cylindrical forms of dielectric material. A few years later, O'Gorman † suggested means of reducing or flattening out the potential gradient by the employment of layers of materials having suitably varying specific inductive capacity. This epoch-making development, to which he gave the term "grading," and the work on similar lines of other investigators, will be referred to later.

The law above referred to was first clearly enunciated by Jona in his classic Paper of 1904. Proof of the formula is given by Russell in his treatise on Alternating Currents, vol. i., p. 170, 2nd edition.

If, in Fig. 49, representing a single-core, metal-sheathed cable,

r=radius of conductor,
R=radius over the complete dielectric,
and r_x=radius of a given point (a) in the dielectric,

the potential gradient or dielectric stress S, when an effective voltage E is applied between conductor and lead-sheath, will—with a dielectric of constant specific inductive capacity throughout its thickness—be a maximum at r, and a minimum at R.

* "Methods of Electrical Transformation." *Minutes of Proceedings of the Institution of Civil Engineers*, vol. 138, p. 478, 1898–9.

† "Insulation of Cables." *Journal I.E.E.*, vol. 30, p. 608, 1901.

These values will be respectively—

$$S_{max.} = \frac{E}{r \log_\epsilon \frac{R}{r}} \text{ volts per cm.,}$$

$$S_{min.} = \frac{E}{R \log_\epsilon \frac{R}{r}} \text{ volts per cm.,}$$

when all dimensions are expressed in centimetres and ϵ is the base of Napierian logs=2·718.

At any intervening point in the dielectric, such as a, it will have an intermediate value—

$$S_a = \frac{E}{r_x \log_\epsilon \frac{R}{r}}$$

Inspection of the foregoing clearly shows that electric stress considerations are of no appreciable moment at low values of E, and it follows that with regard to the requirements of dielectric thickness for low-tension cables, mechanical considerations preponderate. For this reason they increase—according to B.E.S.A. and other standards—with the size of conductor.

At higher working pressures —3 K.V. to 11 K.V.—the mechanical requirements being amply satisfied, the sole consideration is the provision of an ample factor of electrical safety. It is no longer necessary to increase the radial thickness of dielectric with increasing size of conductor, nor is it worth while to vary it for reasons of electric stress, and therefore, according to the B.E.S.A. standards, a constant thickness is employed over the whole range of sizes of conductor for each standard working pressure.

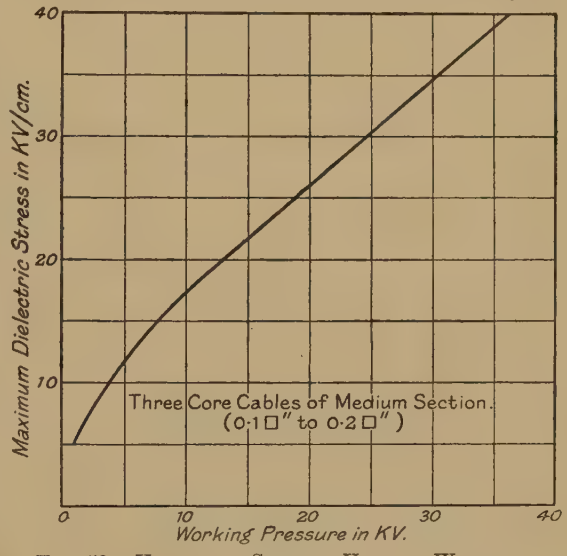

FIG. 50.—VALUES OF $S_{max.}$ AT VARIOUS WORKING PRESSURES.

For higher working pressures than 11 K.V., thicknesses are designed to follow more closely the purely electrical demands, and it need hardly be pointed out that the higher the working pressure, the greater becomes the necessity to force up the maximum electric stress to the highest permissible value in order to minimise the value of R in relation to r. It will further be obvious that the more perfect the

dielectric material can be made, and the greater the precision with which it can be applied, the higher will be the value of the permissible stress with a given margin of safety.

Fig. 50 affords a general survey of the values of maximum stress employed in present-day practice, over the whole range of working pressures up to 35 K.V., these being dependent—as indicated above—on standardised dielectric thicknesses up to and including 11 K.V. and, for higher voltages, on particular designs which may vary to some extent with different makers.

Apart from the desirability, above mentioned, of employing the greatest permissible value of $S_{max.}$, it will be seen from further examination of the for-

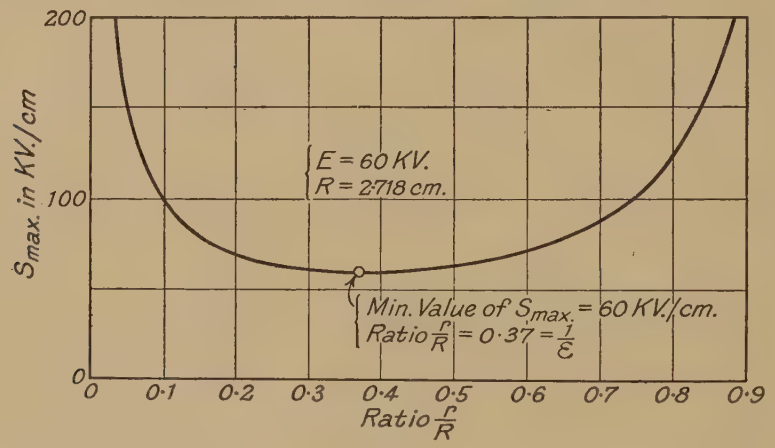

FIG. 51.—VARIATION OF $S_{max.}$ WITH RATIO $\frac{r}{R}$ FOR FIXED VALUES OF E AND R.

mula that with a given value of that factor and also of E, there are certain values of R and r which will entail a minimum overall diameter.

Transposing, we have—

$$R = r\epsilon^{\frac{E}{Sr}}.$$

For R to be a minimum $\frac{dR}{dr} = 0$.

Now $\frac{dR}{dr} = \epsilon^{\frac{E}{Sr}}\left(1 - \frac{E}{Sr}\right)$,

and this equates to zero when $r = \frac{E}{S}$.

Hence $R = r\epsilon^{\frac{E}{Sr}} = \epsilon r$.

If the values of E and R are given we obtain the minimum value of $S_{max.}$, when $\frac{R}{r} = \epsilon$.

In Fig. 51, $S_{max.}$ is plotted against $\frac{r}{R}$, and it can be seen that $S_{max.}$ has a minimum

value of 60 K.V./cm., when $\frac{r}{R}=0{\cdot}37=\frac{1}{\epsilon}$, and increases without limit as $\frac{r}{R}$ approaches zero or unity.

Fig. 52, in which diameters over conductor and under lead-sheath in single cables are plotted against working pressure, for various values of maximum stress, illustrates this from another angle.

Fig. 53 shows yet another practical view of these relations, breakdown pressure being plotted against conductor area for various thicknesses of dielectric, assuming 300 K.V./cm. as the breakdown stress under all of these conditions of R/*r*.

In connection with this logarithmic formula, a great deal of discussion has taken place, and much experimental work has been done. Russell,* in 1907, pointed

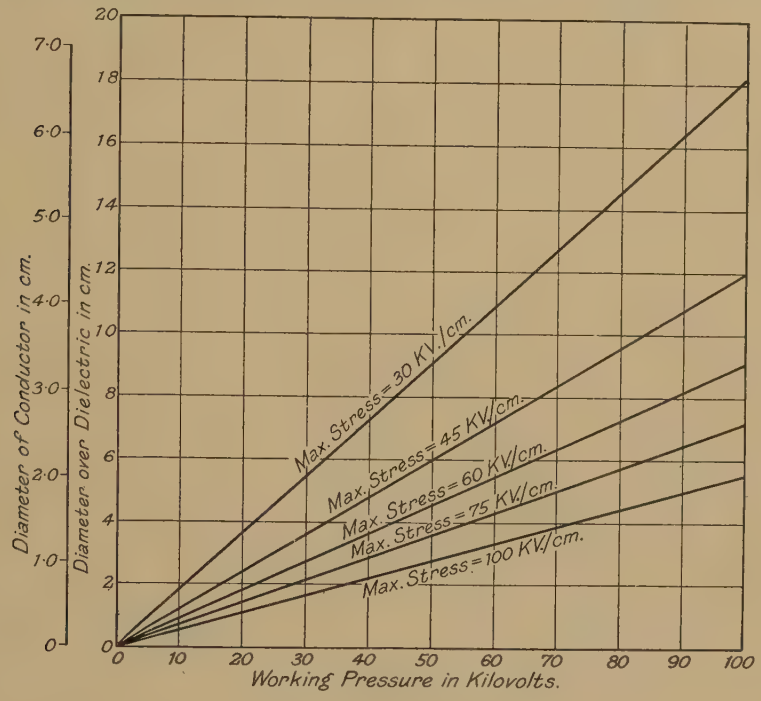

FIG. 52.

out as a logical deduction that if *r* was less than R/ϵ, the breaking down of an annular zone of the dielectric contiguous to the conductor would diminish the maximum stress, and propounded the theory that a disruptive discharge would only occur when the radius of the charred dielectric became greater than R/ϵ. Certain experiments described by Jona (*l.c.*, *ante*), relating to breakdown tests on two single cables having widely different values of R/*r*, were quoted by Russell in support of his theory. The values of $S_{max.}$ at the breakdown pressures found by

* Russell, "Dielectric Strength of Insulating Materials and Grading of Cables." *Jour. I.E.E.*, vol. 40, p. 6, 1907.

Jona were apparently three times as great in the case of a wire of 0·1 cm. diameter as in the case of a cylinder 2·9 cm. in diameter, both having the same radial thickness (1·4 cm.) of paper insulation. Jona really quoted this result of his experiment to show that the ordinary formula does not hold good when R/r is large. Russell, however, pointed out that, calculating on the assumption that the breakdown of the insulation on the thin wire did not take place until the outer radius of the supposedly charred dielectric had become equal to R/ϵ, the maximum stress values in the two cases were in close agreement.

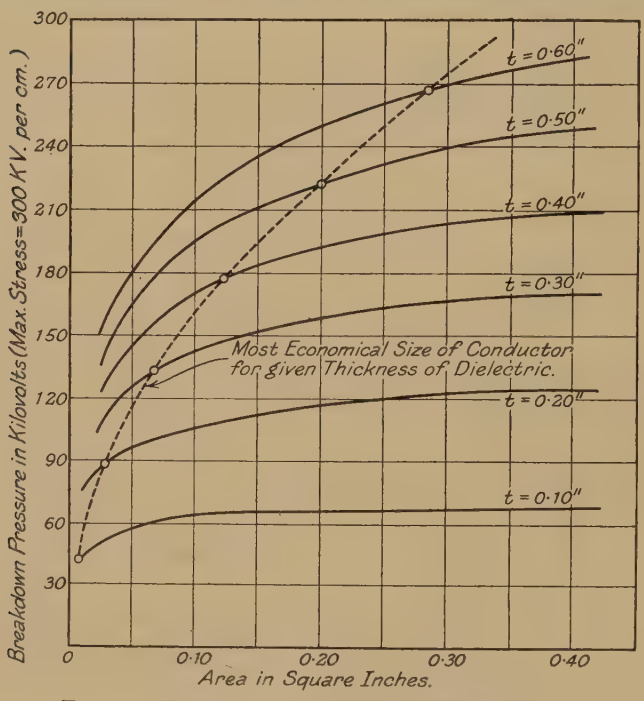

FIG. 53.—VARIATION OF BREAKDOWN PRESSURE WITH CONDUCTOR AREA.

At the time of the discussion on Russell's paper, confirmation of his theory from observations in actual practice was not forthcoming. The present writer, for example, had seen instances of small isolated burnt holes, irregularly distributed about the inner parts of the wall of dielectric, but never unaccompanied by a complete burnout, cause and effect therefore being indistinguishable. Some other contributors strongly contested the theory on the basis of practical experience.

It will be of interest to briefly examine the theory in the light of more recent experimental investigations and theories based thereon.

As an example of a directly opposed view, Fernie,* in 1921, put forward a minimum stress theory as a result of a series of tests on cables having small conductors, with which the Russell theory appeared to be at variance. Fernie's theory need not be discussed here, since its author—to use his own expression †—"does not cling to his own explanation." It was, however, fairly thoroughly discussed in America in the following year in papers by Simons,‡ Middleton, Dawes and Davis,§ and Wiseman‖; the latter paper largely consisting of an analysis of data presented in the other two papers, and by Fernie.

* Fernie, *Beama*, vol. ix., No. 3, p. 244, 1921. † Fernie, *Electrician*, vol. 89, p. 183, 1922.
‡ Simons, "On the Minimum Stress Theory of Cable Breakdowns." *J.A.I.E.E.*, vol. 41, p. 433, 1922.
§ Middleton, Dawes and Davis, "Potential Gradient in Cables." *J.A.I.E.E.*, vol. 41, p. 572, 1922.
Wiseman, "Apparent Dielectric Strength of Cables." *J.A.I.E.E.*, vol. 42, No. 2, p. 165, 1923.

In the course of showing that a theory based on average stress is at least as good as the minimum stress theory, Simons made certain assumptions regarding the existence of overstressed insulation when the remainder of the insulation is in stable equilibrium, and also that the overstressed insulation can support its proportional share of the voltage.

He pointed out that the possibility of the existence of overstressed insulation was not new, and quoted Whitehead's conception regarding a condition of strain in the dielectric material in excess of the electrical elastic limit, producing a conductive state without structural breakdown by creating a tendency for opposite charges of adjacent strained molecules to combine. Whitehead propounded the view that if part of a chain of such molecules strung along a radial line of electric force was not overstressed, the checking of transfer of charges between molecules at the point of change of strain condition would be propagated backward toward the centre, and serve to keep the overstressed portion from breaking down.

Simons did not claim a theory, but urged the need for experimental data.

Middleton, Dawes and Davis, in further development of work published by Middleton and Dawes * in 1914, found, from a wide series of experiments, that the logarithmic law appeared to hold good for cables in which the value of R/r was equal to or less than ϵ, but that, in cases where this value was exceeded, the layers of insulation adjacent to the conductor could be subjected to much greater stresses than the dielectric could normally withstand. On these grounds they suggested a modification of the formula for the latter case.

Wiseman's Paper was of the nature of a critical essay, in which he endeavoured to arrive, from his own and the work of other investigators, at a formula which would embrace the effects of various factors and phenomena which entail divergences from Russell's maximum stress theory, in other words, to distinguish between the true and the apparent dielectric strength. He tabulated the data of the above-mentioned work, to show different points of view, which indicated generally that neither the minimum nor the average stress theories were tenable. He made two assumptions in further interpreting the data. Firstly, one which is not generally accepted by other investigators, viz., that ionisation occurs in a solid dielectric; secondly, that the dielectric strength is a function of the size and shape of the electrodes, a principle which does not admit of dispute (see p. 185). In the case of a single cable it is a function of the square root of the outer radius of the dielectric. In the formula evolved, expressions for these two factors are combined with the term $r \log R/r$ as in the Russell formula, *i.e.* relating to the shape of the electrostatic field.

During the period between the early days when the simple logarithmic law was first being enunciated, mathematically proved and discussed, and the recent epoch of scientific research, many writers and speakers have referred to it, and to Russell's deduction from it, almost as though both were impugned.

If it is borne in mind that the law is obviously only applicable to isotropic dielectrics, and if the wide divergence between the theoretical material and the

* Middleton and Dawes, "Voltage Testing of Cables." *Trans. A.I.E.E.*, vol. 33, p. 1184, 1914.

heterogeneous and/or physically or chemically susceptible character of most of the materials experimented upon (for example, varnished cambric is both laminated and cellular in structure, and also liable to chemical change under high electric stress conditions) is appreciated, the need for empiricising the formula to adjust it to the imperfections of commercial dielectrics will be quite apparent.

Further, although Russell's theory regarding the case where r is less than R/ϵ has lacked precise demonstration because of the inherent difficulty of experimentally producing the required conditions, there would appear to be a traceable connection between his conception and the observations of Fernie on the apparent dielectric strength of cables having small conductors, the conception of Whitehead and arguments of Simons regarding the overstressing of the inner part of a dielectric without failure, and the demonstration by Middleton, Dawes and Davis of appreciable difference in breakdown values between different geometrical conditions of disposition of the dielectric.

It is clear, of course, that Russell's reference to a " charred " zone must have been intended to be more or less figurative, and to embrace any—even remotely—comparable effects.

It appears to be confirmed that effects of the kind referred to do occur, and unless we are to assume a sort of exaltation of the breakdown voltage of the material under the conditions in question, some deteriorating effect must occur; and it is conceivable that, given an isotropic dielectric, and ability to maintain the state of overstress needed for the purpose, it might proceed even to the advanced state which Russell pictured.

Wagner, in connection with his brilliant work on the breakdown of solid dielectrics, evolved the theory—which appears to be supported by his tests—that the less stressed portions of the path of the current through the dielectric prevent the current from increasing excessively, and that breakdown only occurs when the whole of the path has become thermally unstable.

This theory would appear to be broadly analogous to Whitehead's conception, referred to on p. 217.

STRESS DISTRIBUTION

We have, so far, only considered the simple case of a single or concentric cable in relation to the distribution of electrostatic stress between the central conductor and a metal sheath or an outer conductor, in which case the concentrically arranged sheath fulfils the important function of ensuring symmetry of such stress distribution by forming a boundary to the electrostatic field.

In a three-phase 3-core cable, however, the electrostatic polyphase field rotates at uniform angular velocity about the geometric centre of the cable in a manner analogous to the rotation of the magnetic field in an induction motor.

Höchstädter * has shown by diagrams that—regarding a cross-section of a 3-core cable—the potential difference between the points of contact of the three

* *Elekt. Zeits. Abstract*, " Electrician," 1916, p. 209.

insulated cores may consequently be equal to 87 per cent. of the line voltage. He points out that this sets up stresses tangentially to the core insulation, and as these operate in and about the position of maximum temperature in the cross-section, their effect is very undesirable.

There appears to be definite evidence from practical results that charring of the fibrous interstitial padding which is used in the construction of multicore cables is sometimes caused, and there seems to be little doubt that, apart from actual circulation of current due to comparatively low resistance paths (which should be negligible in a well-made cable) between these points of potential difference, and ionisation effects in air cavities in the padding (which are practically unavoidable in cable of ordinary construction), there is an undesirable distortion of the electrostatic field

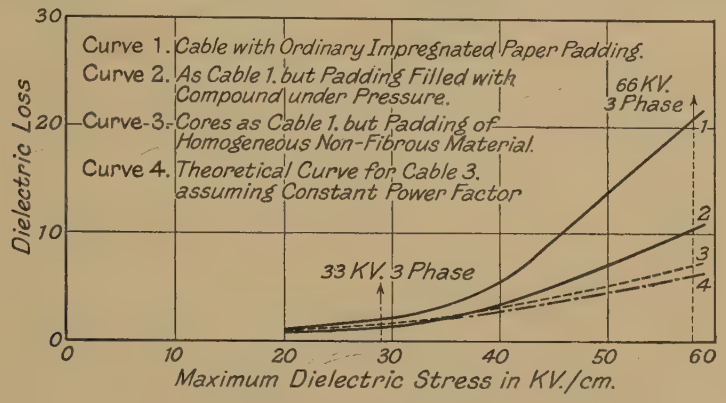

Fig. 54.—Effect on Loss/Stress Curve of reducing Air Spaces in Padding Materials.

due to the permittivity of the padding being appreciably lower than that of the paper insulation of the cores.

Clark and Shanklin,* gave the opinion that " these tangential stresses, occurring as they do in the hottest part of the cross-section, are a weak point in three-conductor design, and will probably be the limiting feature of the maximum voltage rating that will be reached in the future.

Atkinson,† in deducing practical applications of the data resulting from his brilliant work on the exploration of the dielectric field in 3-core cables, points out the great importance of the tangential stresses, and says that they are large as compared with the average stress throughout the insulation, and even as compared with the maximum stress values at the conductor surface.

He further says : " Improvement in this portion of the dielectric has not in the past kept pace with improvement in the insulation near the conductors, and probably can still not do so in the future. Doubtless, therefore, stresses in this portion of the cross-section will become more and more the limiting condition on cables of the usual three-conductor form."

* " Insulation Characteristics of High Voltage Cables." *Trans. A.I.E.E.*, vol. 36, p. 447, 1917.
† " The Dielectric Field in an Electric Power Cable." *Proc. A.I.E.E.*, vol. 38, p. 971, 1919.

The author has proposed,* and developed on a commercial scale, a construction which goes far to obviate the above-mentioned disadvantages and limitations, which consists in replacing the usual fibrous filling or padding material with a homogeneous non-fibrous air-free material of the vulcanised bitumen type. Details of construction are given under "Manufacture," vol. ii., but for the present purpose it may be stated that extruded strips of suitable cross-section are laid up with the insulated cores by special means which ensure the elimination of air cavities and close contact of the filling with those parts of the core and overall insulation to which it is contiguous.

The effectiveness of this construction is well illustrated by the comparison of loss/stress characteristics plotted in Fig. 54.

The three 33 K.V. cables to which the curves relate were identical as regards size and thicknesses of impregnated paper insulation on cores and overall. The building of the dielectric was by the precision method, referred to under "Manufacture," Vol. ii. The comparison, which is self-explanatory, therefore, relates to the padding or filling in the central and in the three outer interstitial spaces. *Inter alia*, it will be seen that in ordinary construction between 60 per cent. and 70 per cent. of the total losses occur in the padding spaces at stresses entailing appreciable ionisation.

This confirms a prediction made by Mr A. J. Tracey, of Messrs Johnson & Phillips, in the course of an I.E.E. discussion in London on "The Use of the Electrostatic Wattmeter for the Measurement of Dielectric Losses in Cables." † Mr Tracey said that, "in his opinion if it were possible to isolate losses in three-phase cables, it would be found that 75 per cent. were due to the fillers" or padding in the interstices between the insulated cores.

The possibility of isolation would appear from Fig. 54 to be attained simultaneously with the possibility of elimination, at least, so far as the heavy preponderance is concerned.

Reverting to the broad question of the distribution of the electrostatic stresses in a high-voltage 3-core cable, it has long been realised that, in view of the great difficulty and complication entailed in its mathematical investigation, experimental exploration of cross-sections represented by large-sized models is likely to yield more accurate results.

O'Gorman, in his Paper on "Cables" in 1901 (*l.c.*, *ante*), referred to a suggestion made to him by Professor Perry which entailed the placing of a thin sheet of high resistance metal over an enlarged model representing conductors and lead sheathing (the latter being maintained at correct relative potentials), so that the distribution of potential might be traced by the use of needles connected to a galvanometer.

Later, Thornton ‡ applied to this electrostatic case the well-known hydrodynamic stream-line method used by Hele-Shaw § for the solution of otherwise indeterminate problems in the distribution of magnetic fields of force.

* Patent Nos. 107073/16 and 22125/25.

† *Electrician*, vol. xciii., No. 2431, p. 695, 1924.

‡ Thornton and Williams. Paper read before the British Association at Winnipeg. *Electrician*, Sept. 3rd, 1909.

§ Hele-Shaw and Hay, *Phil. Trans.*, vol. xcv., pp. 303–27.

Atkinson, in his 1919 Paper on "The Dielectric Field in an Electric Power Cable" (*l.c.*, *ante*), described experimental apparatus consisting of cylindrical electrodes, representing the cable conductors and metallic sheath, arranged in a wooden tub containing a liquid electrolyte (water of fairly high-resistance), representing a homogeneous dielectric together with an exploring device containing potential electrodes which was suspended from the tracing point of a pantograph. The drawing-point of the pantograph indicated on a representative drawing the relative positions of the electrodes representing the cable conductors and the potential electrodes of the exploring device for each individual observation.

Certain precautions were taken with regard to avoidance of error in the measurements due to phase displacement, distortion of field by the measuring current, etc. Experiments were also made, for check purposes, on an actual cable having potential wires distributed around the periphery of each insulated core.

Very valuable information was derived by Atkinson from these experiments. Reference should be made to the original Paper for details of the conditions of test and results of experiments.

For the present purpose, perhaps the most important results relate to the Author's finding that Russell's formula for the maximum stress between eccentric cylinders applies very closely to the relation between one core of a 3-core cable and the lead sheath (this being, of course, a single-phase field), and is unaffected by the proximity of the other two conductors.*

The formula is not quoted in the Paper, but is evidently that given by Russell in his "Alternating Currents," vol. 1, 2nd edition, p. 170 (28), for the maximum stress, between two parallel but eccentric cylinders, the larger of which is hollow and surrounds the smaller.

Under these conditions the value of the maximum stress is :—

$$S_{max.}=\frac{v_1-v_2}{a\omega_1}\left[\frac{b^2-(a-c)^2}{b^2-(a+c)^2}\right]^{\frac{1}{2}}$$

where a=radius of smaller cylinder, at potential v_1
b=radius of larger cylinder, at potential v_2
c=distance between their centres,

and $\cosh \omega_1=\dfrac{b^2+a^2-c^2}{2ab}$.

In Fig. 55, reproduced from Atkinson's Paper by kind permission of the author and the American I.E.E., the lower curve is calculated from the above formula for maximum stress between eccentric cylinders.

The author states that his results check within 2 per cent. of the calculated values.

(For the purpose of the diagram the values of maximum stress have necessarily

* It may be noted that Shanklin and Matson ("Ionisation of Occluded Gases in High Tension Insulation," *Proc. A.I.E.E.*, vol. 38 (No. 2), p. 163, 1919) somewhat similarly found that the stress corresponding to the commencement of ionisation in one core of a 3-core cable was independent of the proximity of the other two conductors.

to be given in terms of average stress, as indicated thereon. This might perhaps be better expressed as the ratio of maximum to average stress.)

The middle curve is calculated similarly from the simpler formula for single (or concentric) conductor cable, and the upper curve shows the ratio between the values of the stresses in the two cases.

It will be noted that the percentage difference is very small compared to the ordinary factors of safety provided for in high-pressure cables.

The foregoing references to the work of Atkinson render it opportune to refer here to the much-discussed effect of stranding on the maximum stress in a cable dielectric, because, so far as the author is aware, no other investigator has made *direct* measurements bearing on the subject.

Stranding virtually alters the surface of the hypothetical smooth cylinder to which the logarithmic formula relates into a spirally grooved or corrugated one,

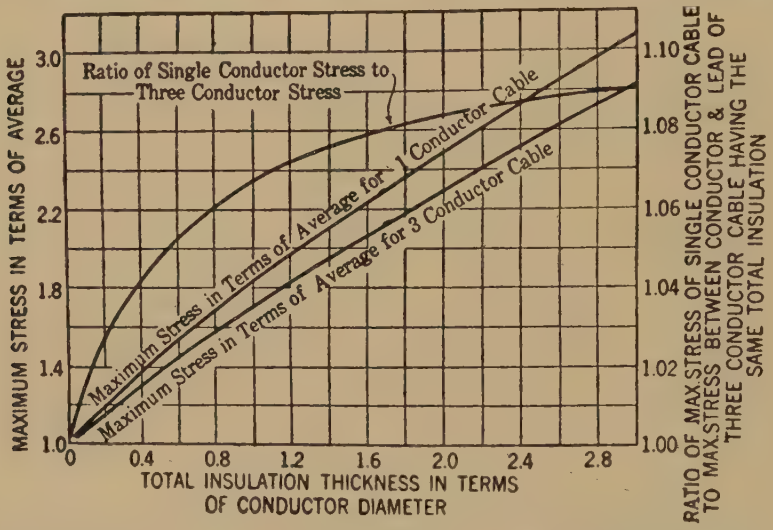

FIG. 55.—CURVES SHEWING RELATION BETWEEN STRESS OF THREE-CONDUCTOR CABLE AND STRESS OF SINGLE-CONDUCTOR CABLE AND BETWEEN MAXIMUM AND AVERAGE STRESS OF EACH.

and in view of the well-known electrostatic " edge " effects, it would appear that the maximum stress at the inner boundary of the dielectric would be increased.

It was suggested many years ago by O'Gorman * that it would be advantageous from this point of view to sheathe the conductor with lead. Jona (*l.c.*, *ante*) experimentally and mathematically (on the basis of a formula due to Prof. Levi-Civita) investigated the matter, and found that theoretically the effect of stranding was generally to increase the maximum stress in the dielectric by about 20 per cent., and although his experiments, based on brush discharges from the surfaces of solid wires and strands of equivalent diameter, showed no appreciable difference,† he adopted the method of covering the stranded conductors of his " graded " cables with a thin lead tube.

* O'Gorman, Patent No. 21170/1901. † Russell, " Electric Cables and Networks," p. 281, 3rd Edn.

Atkinson, in his 1919 Paper (*l.c., ante*), gave results of tests which closely confirmed Jona's calculated values, but found no difference between 7-strand and 19-strand conductors. His results also appeared to indicate that when R/*r* was large, the percentage increment of stress due to stranding was greater, and when small, less than the average rough value of 20 per cent.

Shanklin and Matson stated on the other hand that they had made a close study of smooth and stranded conductors, and had never found any difference between their effects. Their criterion—the commencement of ionisation in a dielectric subjected to increasing stress—could not, however, be considered as reliable as the direct voltage measurements made by Atkinson in his exploration of the dielectric field by means of models.*

While appreciating that Atkinson's exploration methods of research are particularly suitable for the isolated and untrammelled investigation of such a point

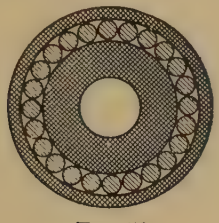

FIG. 56

Inner lead tube	0·256 in. bore, 0·140 in. radial.
Conductor	24/0·082 in.
Outer lead sheath	0·05 in. radial.
Complete diameter	0·80 in.

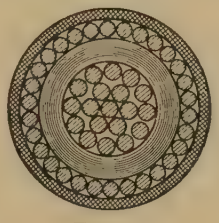

FIG. 57.

Inner conductor	19/15 S.W.G.
Paper layer	0·117 in. radial.
Conductor	30/0·053 in.
Outer lead	0·05 in. radial.
Complete diameter	0·80 in.

as this, the paucity of data in the literature of the subject on what would appear to be a substantial feature of its perspective is remarkable. No attempt to empiricise the simple formula in this direction appears to have been made.

A modification of the lead-sheathing principle above referred to has been utilised by the author in the form of a hollow conductor † for use in cases where the most economical size of conductor (r=E/S) gives a larger sectional area than is required for current-carrying purposes. Fig. 56 shows such a conductor designed for a working pressure of 50 K.V. and a maximum stress in the dielectric of 50 K.V. per cm., and having an effective area of ·127 sq. in. The required number of copper wires are stranded on a substantial lead tube and are then sheathed with a thin covering of lead. This construction not only provides a smooth exterior surface and the economical attainment of the required diameter, but also ensures retention of shape when the conductor is bent, by reason of the fact that the wires slide freely in the annular space between the two lead tubes. This sliding is facilitated by lubrication, although in practice this does not appear to be essential. The utilisa-

* As a sidelight on the matter, it is interesting to note that Peek's factor for stranded conductors in his well-known formula relating to the disruptive critical voltage of air is 0·85, as compared with unity for a smooth clean conductor.

† Beaver and Claremont, Patent No. 20549/1914.

tion of the central tube for cooling purposes was originally thought to be a possibility, but this has not been tried.

Fig. 57 shows a modification of Fig. 56 wherein, for similar conditions of working pressure and maximum stress in the dielectric, a 15 sq. in. " split conductor " may be accommodated within the same external diameter. This composite conductor has a radius which corresponds to the most economical construction for a working pressure of 50 K.V. and a maximum stress of 50 K.V. per cm.

GRADING

From the preceding study of the law of potential gradient, it has been seen that the distribution of stress throughout a homogeneous dielectric is such that a curve would result from plotting it against radius, and that, because of this lack of uniformity of distribution the breakdown voltage would be less than the product of its electric strength and its thickness. The obvious corollary is that if some means of compensating for the variation could be adopted, without countervailing disadvantages, so that the curve became a straight line, an important contribution to dielectric efficiency would be made. For various reasons, which will be obvious on close consideration of all the factors in the case, this ideal can only be more or less approximated to in cable work.

Various proposals to this end have been made from time to time, and brief reference has already been made to that of O'Gorman (see p. 212), who suggested the word " Grading " as a generic term " for a method of adjusting the specific capacity, dielectric strength and conductivity of the covering of a cable so that the materials composing it occupy the best possible positions, whether for resisting puncture or diminishing the energy loss in the insulation," and pointed out that this could be accomplished by varying the materials of which the successive layers comprising the whole dielectric were composed. He discussed each of these three alternative adjustments, practically dismissing that of dielectric strength by pointing out the futility of introducing layers of material which rank high in this respect without due regard to the effect of their specific capacity.

With regard to conductivity, he suggested certain modifications of impregnating media for paper insulation (which were, unfortunately, quite impracticable) with the object of ensuring that the fall of potential in each layer was minimised and uniform. It is apparent from the Paper that this method was designed for the continuous current case, and that the disturbing effects of temperature coefficients of the components on the conductivity (or insulativity), and consequently on the potential gradient, were appreciated by the author.

With regard to grading by the utilisation in layers of substances of different specific inductive capacities to obtain uniform stress throughout the dielectric under alternating pressures, the principle was clearly set forth that the specific inductive capacity of each of the elementary condensers constituted by each layer of substance should be such that they should have the same capacity in spite of the differ-

ences in their areas; so that, as they would all receive the same charge, the same difference of pressure would exist between their inner and outer surfaces, and therefore the stress throughout the dielectric would be uniform.

O'Gorman suggested and patented * the use of layers of paper impregnated with compounds having different specific inductive capacities, such variations being obtained by the admixture of castor-oil, in varying proportions, with the usual resin-oil type of impregnating medium.

These proposals were regarded with diffidence by both cable-makers and users, the chief fear being with regard to the effects of diffusion in equalising the permittivity of the layers.

On this point, however, in a letter to the Editor of *Electrical Engineering*, dated 28th November 1907, Mr O'Gorman stated that "the dissection of a graded cable shewed that when not in use no *de*grading had set in in five years; on the other hand, when the cable is in use there is a powerful agency at work which will not only keep the grading, but improve it . . . if there is any place in the cable insulation where the stress is higher than elsewhere, that is the very place to which the high capacity materials will move under the electric forces until the stress is rendered uniform by their automatic marshalling into their proper situations." † It may be mentioned that in his original Paper O'Gorman referred to experiments he had in view, in which the properties of the paper were to be varied by loading with pigments to different extents.

Almost concurrently and apparently quite independently (no mention being made by O'Gorman of other workers in this field), E. Jona, of Messrs Pirelli & Co., Milan, appears to have been developing a graded cable. In a letter to the Editor of *Electrical Engineering*, dated 30th November 1907, Mr Jona said: "In his very interesting and learned Paper before the Institution of Electrical Engineers in March 1901, Mr O'Gorman was the first, I believe, to publish a theory on potential gradients in cables, and the manufacture of cables with graded dielectrics, but I had been engaged on the same question as far back as 1896-7. In 1898 the Edison Company of Milan laid an experimental cable, made with a mixed insulation of rubber and paper, a short time after Messrs Pirelli & Co. applied for an Italian patent for this cable, and in 1900 a cable of this patented type was exhibited by this firm at the Paris Exhibition, working at 28,000 volts, which was fairly high for the period."

In the Italian patent, which is dated 20th April 1900, there is, however, no mention of grading in the "mixed insulation of rubber and paper" above referred to, and it would seem clear from the wording of the specification that any relation between the specific inductive capacities of the two kinds of insulating material referred to was not fundamental to the design. It is also interesting to note that the lead sheath of the stranded conductor referred to on page 222 was not used

* O'Gorman's "Grading" Patent (No. 1568/1901) was acquired by Messrs W. T. Glover & Co., Ltd.

† The author has never seen the slightest evidence of this suggested automatic grading in cable dielectrics. This is confirmed by statements made by Clark and Shanklin (*l.c.*, *ante*), and by Middleton, Dawes and Davis (*l.c.*, *ante*).

in the cable exhibited in Paris in 1900 (referred to above), nor is there any reference to it in the Italian patent specification above mentioned.

In 1904, however, at the International Congress held at St Louis, Jona read his classic Paper giving considerable data on single-core cable which he had made and tested, in which layers of vulcanised (specially compounded) rubbers and impregnated paper were utilised in the true sense of grading.

At the Milan Exhibition in 1906 a length of this graded cable, details of which are given below, along with a diagrammatic section, Fig. 58, was exhibited under a frequently applied test pressure of 150,000 volts.

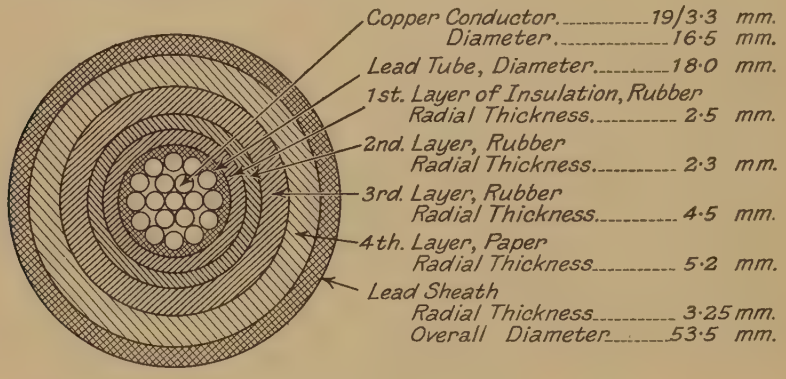

Fig. 58.

The conductor consists of 19 strands of copper wire, each having a diameter of 3·3 mm., and is sheathed to a total diameter of 18 mm. with lead.

The layers comprising the dielectric are as follows :—

1st layer—	Rubber compound	2·5	mm.	radial	thickness,	specific inductive capacity	6·1
2nd ,,	,,	2·3	,,	,,	,,	,,	4·7
3rd ,,	,,	4·5	,,	,,	,,	,,	4·2
4th ,,	Impregnated paper	5·2	,,	,,	,,	,,	4·0

Russell * has mathematically investigated the requirements relating to the proportioning of an isotropic dielectric and the effects of using materials having different specific inductive capacities, etc., in the form of a composite dielectric, assuming leakage current through the dielectric negligible in comparison with the capacity current.

For the Jona cable above described he calculates the maximum stresses in the four layers of dielectric material above mentioned to have been 124, 132, 123, and 97·4 K.V. per cm. respectively, at the test pressure of 150 K.V., as compared with a value of $S_{max.}$ of 174 K.V. per cm. for an isotropic (or homogeneous) dielectric.

In his Paper on " Cables " (*l.c.*, *ante*) the author, after alluding to the practical difficulties attending the methods of O'Gorman and Jona, expresses preference from the cable-manufacturing point of view for the " intermediate conducting sheath "

* *Electric Cables and Networks*, 3rd edition, pp. 263 *et seq.*

method of grading or distribution of potential in the dielectric, and proceeds to discuss the pros and cons of "intersheath *v.* capacity grading."

The intersheath method of grading cable dielectrics may be broadly defined as consisting of the interposition of metallic layers in the wall of dielectric material, and of "anchoring" them at suitable predetermined potentials. It may here be remarked that the prototype of the intersheath graded cable is the condenser type of terminal or "bushing" now commonly used on transformers and very high voltage apparatus, which was developed in America about the beginning of the present century. The principle had been advocated by Ryan, Nagel, and others in 1904, and was subsequently described in considerable detail by Reynders * in 1909.

As the length of transformer terminal does not exceed a few feet, the application of the intersheath principle in its construction is much simpler than in the case of a cable in which the length is unlimited. In the former case the capacities of the condensers, constituted by the layers or annular components of the insulation, are easily capable of equalisation by trimming back the metal foil layers to an extent depending upon the radius at which they are applied; whereas in the case of a cable the ratio of length to radius may be practically infinite, entailing in consequence the use of external arrangements to accomplish the above-mentioned "anchoring" of the intersheaths at their designed potentials.

So far as the author is aware, the first suggestion regarding the embodiment of intersheaths connected to transformer tapping points in cable construction was made by Prof. J. T. Morris, in a communication on Russell's 1907 Paper (*l.c.*, *ante*). The suggestion appears to have been of a tentative character, however, as it showed no evidence of essential features of design, *e.g.*, relative spacing of sheaths, resultant distribution of potential, provision for carrying charging current, etc., having been considered. Application of the principle in other branches of electrical engineering has been suggested; for example, the British Thomson-Houston Co. was granted a patent † in 1907 for a method of applying it to the windings of high voltage machines.

From the cable dielectric aspect the intersheath method obviates the manufacturing complications incidental to the use of a number of more or less delicately adjusted materials as required by the "capacity grading" methods of O'Gorman and Jona, because it is obviously easier to ensure a high standard of uniformity and dielectric strength in a single dielectric material. On this point the user would also be more inclined to pin his faith to a single material of proved history in preference to a combination of materials which might (as for example in the case of rubber and resinous or oily impregnating compounds) react upon each other.

Other manufacturing advantages pointed out by the author related to the avoidance of the electrostatic discontinuity difficulty between layers of material of varying specific inductive capacity to which Osborne drew attention in his Paper on "Potential Stresses." ‡ In this connection the author has proposed §

* A. B. Reynders, "Condenser Type Insulation for High Tension Terminals." *Trans. A.I.E.E.*, vol. xxviii. (1), p. 209, 1909.

† No. 25834/1907.

‡ *Trans. A.I.E.E.*, vol. 29, p. 1553, 1910.

§ Beaver and Claremont, Patent No. 19882/1914.

the use of impregnated paper with a metallised surface next to conductors to ensure perfect contact between conductors and dielectric, which includes in the present case the thin intersheath conductors and the dielectric on either side of them.

Again, the form of intersheath conductor preferred by the author, viz., a thin lead tube, not only presents smooth surfaces and gives facilities for uniformly close application over the dielectric, but also affords the advantage of allowing tests to be made on the cable after each portion of the dielectric is applied.

The minimum practicable thicknesses of such tubes will, in most cases, provide sufficient sectional area to carry the charging current, although in this connection it has to be remembered that each successive sheath carries the sum of the currents in preceding sheaths.

With reference to the actual intersheath design, calculations show that when the conditions of working voltage E and maximum stress $S_{max.}$ are such that the ratio of R/r is less than 5 the commercial usefulness of the method approaches its limitations.

On this minimum basis the following comparison may serve as an example.

Taking the case of an ungraded cable for a working pressure of 100 K.V. and fixing the maximum allowable stress in the dielectric at 40 K.V. per cm., the most economical size of conductor will have a radius of $r=\frac{E}{S}=2{\cdot}5$ cm.

The sectional area of such a conductor would be approximately 2·25 sq. in., and a hollow conductor would obviously be required.

The radius over the dielectric would be :—

$$R=r\epsilon=6{\cdot}8 \text{ cm. or } 5{\cdot}36 \text{ in. diameter over dielectric.}$$

Taking the alternative graded cable, with one intersheath, and assuming the ratio $R/r=5$, and a division of the total radial thickness of the dielectric into two equal parts, the voltages across the halves would be 41·78 K.V. and 58·22 K.V. respectively, for equal values of $S_{max.}$ in both parts of the dielectric.

The conductor radius is then :—

$$r=\frac{E}{S\log_\epsilon \frac{3}{1}}=\frac{41{\cdot}78}{40\log_\epsilon 3}=\cdot 953 \text{ cm.}$$

This gives a conductor area of ·325 sq. in., and if this exceeds the current density requirements a hollow conductor may be used or a metal of lower conductivity, *e.g.*, aluminium, may be employed.

The radius over the first dielectric will be :—

$$R_1=r\times 3=\cdot 953\times 3=2{\cdot}86 \text{ cm.}$$

Taking the radial thickness of the intersheath as ·05 in.=·127 cm., the radius R_2 over the second dielectric will be :—

$$R_2=r_2\epsilon^{\frac{E}{Sr_2}}=2{\cdot}987\epsilon^{\cdot 49}=4{\cdot}87 \text{ cm., or } 3{\cdot}83 \text{ in. diameter.}$$

For this particular set of conditions therefore an advantage of more than $1\frac{1}{2}$ inches in diameter is gained by the interposition of one intersheath in the dielectric.

Fig. 59 illustrates a general comparison between the following paper insulated cables.:—

(*a*) Ungraded.
(*b*) Graded with one intersheath, } evenly spaced in the dielectric.
(*c*) Graded with two intersheaths, }
and (*d*) Jona's rubber and paper graded cable, above described.

The working pressure of 75 K.V. was chosen for this comparison because it appeared to be—judging from the stress values—the highest safe working pressure of the Jona cable.

The maximum stress of 45 K.V. per cm. for (*a*), (*b*), and (*c*) was selected because it approximately corresponded to that in the paper component (outer layer) of Jona's graded dielectric, besides being reasonably near the advisable limit under working conditions.

The comparison between (*a*), (*b*), and (*c*) is direct, the conductor radius in each case being the most economical.

In the case of (*a*) a hollow conductor would be desirable, and in (*b*) an aluminium conductor would be preferable, while (*c*) could have a stranded copper conductor.

The result of the intersheath grading is shown to be a reduction in diameter—as compared with the ungraded cable—of the order of $1\frac{1}{4}$ inches but it is also extremely improbable that for the conditions in question, (*c*) would have any practical advantage over (*b*), because considerations outside the cable itself (referred to later) have to be taken into account.

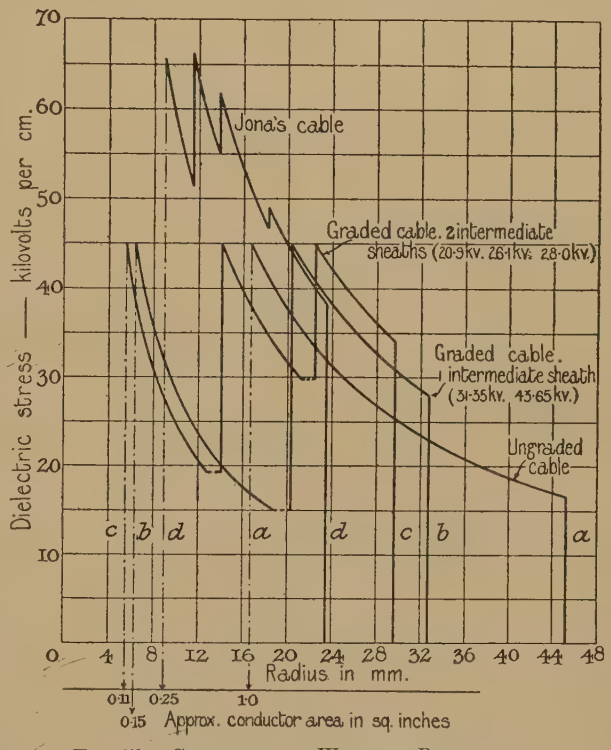
Dielectric stress — kilovolts per cm.
70
60
50
40
30
20
10
Jona's cable
Graded cable. 2 intermediate sheaths (20·9 kv. 26·1 kv. 28·0 kv.)
Graded cable. 1 intermediate sheath (31·35 kv. 43·65 kv.)
Ungraded cable
c b d a d c b a
0 4 8 12 16 20 24 28 32 36 40 44 48
Radius in mm.
0·11 0·25 1·0
0·15 Approx. conductor area in sq. inches

Fig. 59.—Cables for a Working Pressure of 75 Kilovolts.

The comparison of (*d*) with (*a*), (*b*), and (*c*) is only general, the radius of conductor not being the most economical (this, in the type of cable in question, not being determinable), and the maximum stresses in the various layers being appreciably higher.

It serves, however, to illustrate the effect in the capacity method of forcing up the dielectric stress, and of increasing the number of layers, in which direction O'Gorman's proposals regarding variable treatment and composition of paper would, if successful, offer considerable advantage over layers of vulcanised rubber, which of necessity have to be thicker and entail difficulties with regard to correct vulcanisation.

With regard to the distribution of potential in the intersheath type of dielectric, it will be clear from the diagram that this can be varied by altering the position or relative positions of the sheath or sheaths in the radial thickness of the dielectric as required to suit potential anchoring arrangements. (Incidentally, values of S, other than $S_{max.}$, are similarly capable of alteration.)

With regard to anchoring the potential of intersheaths various methods for both continuous and alternating current cables have been patented by Tanner & Claremont.* Briefly, the former consist of taking tappings from generators at the desired potential points or by adding suitable external resistances in parallel with the units comprising the dielectric. In the alternating current case, tappings are taken from transformers at the required voltage points, or separate compensators or choking coils are used either across the mains or between main conductors and intersheaths.

Another method, patented by the Land and Sea Cable Company,† proposed the use of suitable external capacities in the form of condensers connected between the intersheaths.

It will be obvious from the foregoing that while the intersheath type of grading has the advantage of simplicity in manufacture and of proved durability of the dielectric material, it is at a disadvantage with regard to methods of use, involving as they do modifications to connected apparatus, *e.g.*, tappings on transformers and generators or the installation of special apparatus such as condensers, compensators, choking coils, resistances, etc.

The interesting proposals put forward in 1923 by Major A. M. Taylor ‡ in connection with his 6-phase/3-phase system of high voltage power transmission would, however, if they came to fruition, go far to wipe out this general disadvantage.

Broadly, Major Taylor's scheme involved the utilisation of the intersheaths —hitherto only regarded as potential distributors—for current carrying purposes in connection with a system of circuits working at superposed pressures totalling voltages which were outside the range of 3-core construction, the conductors of triple concentric cables being connected to appropriate points of the system.

In Taylor's 6-phase/3-phase system the high tension transmission is three-phase, and there are two cables per phase, each of these cables being a 3-core concentric type of cable. The six cores of these cables are connected to the six phases of the double star connected secondary of a transformer, whose primary is connected to the three-phase generating system. The secondary is wound for 30 K.V. per

* Patent Nos. 27858/08 and 27859/08. † Patent No. 25058/05.

‡ "The Possibilities of Transmission by Underground Cables at 100,000/150,000 Volts;" *Jour. I.E.E.*, vol. 61, p. 220, 1923.

phase, and is earthed at a point midway between two adjacent phases, as shown in Fig. 60.

The cables, if connected to transformers at the receiving end in a similar manner, will constitute three sets of six-phase transmission, in which the inner core of the cable is at a potential of 60 K.V. with respect to earth, and the other cores at the potentials shown in Fig. 60, *i.e.* the cable considered as a single-core cable is a 60 K.V. intersheath cable, in which the six-phase system supplies the intersheath charging currents as well as the load current on the six-phase system.

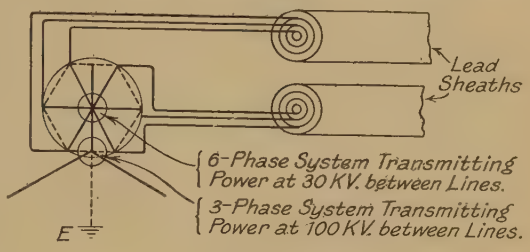
Lead Sheaths
6-Phase System Transmitting Power at 30 KV. between Lines.
3-Phase System Transmitting Power at 100 KV. between Lines.
E

Fig. 60.

If the central cores of these pairs of cables be connected so that they constitute a three-phase system, they may be connected to a three-phase transformer, whose secondary is wound for 60 K.V. per phase, and whose primary is connected to the generating system, and the three-phase system can then be used for transmitting additional power at a pressure of 100 K.V. between lines.

In a few words the principle is that of transmission at 100 K.V. by intersheath cables in which the intersheaths serve the double purpose of adjusting the potential gradient in the dielectric and also of transmitting power.

An advantage accruing from the proposed construction of the cable, which would dispose of certain criticism made in connection with the present writer's original proposals, is that the intersheaths must necessarily be heavy, and hence there is no danger of the sheath being fused, and also there is only a very small voltage drop due to the capacity current flowing along these intersheaths, and hence there is no need to make tapping points along the line to adjust the sheath potential to its correct value. Also, if one phase of the high-tension transmission breaks down, power can still be transmitted by the four other cables using the six-phase system.

Certain details of tests on an experimental cable of this type have been published in a recent article * written by Major Taylor.

Discussion of the merits or demerits of the proposals as a whole are outside the scope of this work; but so far as the cables are concerned (in relation to the commercial feasibility of the intersheath method of grading), it is clear that the dual rôle which the concentrically arranged conductors are designed to fulfil, puts the whole set of considerations regarding intersheath grading on an entirely different footing.

More recently, S. Silbermann † has proposed to construct a cable of the intersheath graded type, in which the electrostatic capacities of the various layers of insulation comprising the dielectric are equalised by connecting each of the condensers which they constitute to other condensers, similarly formed in the interior of the main conductor, which is large and hollow.

* "150 K.V. Cable Tests," *Electrician*, vol. 94, No. 2455, June 1925. † Patent No. 218279/24.

The compensating means in this case, with whatever complications they may entail in manufacture and jointing, are—comparable with the case of the well-known condenser terminal—contained within the cable. It remains to be seen whether the balance of technical and economic advantage is in favour of this or of external apparatus, as referred to above.

Apart from the pros and cons already mentioned, a broad survey of the whole question of grading will show that it is hardly likely to come into commercial range at working voltages below, say, 80 to 100 K.V., especially in view of the rapid advance which has been made during the past few years in the improvement of the efficiency of high-voltage dielectrics.

Single Core Cables

Clearly, grading can only be effectively carried out on cables in which the electrostatic field is symmetrical about the axis of the conductor, *i.e.* single or concentric cables; and in the course of raising working pressures and taking maximum stresses to their permissible limit compatible with sufficient margins of safety, a stage will first be passed which will be dependent on limits of weight per length, (handleability) of 3-core cables.

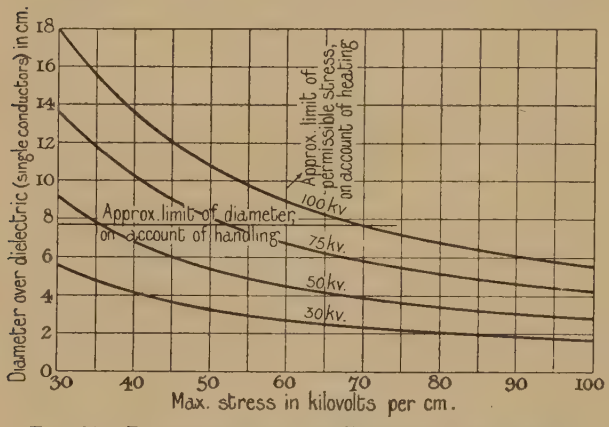

Fig. 61.—Diameters over the Dielectric of the most Economical Cables for given Working Pressures at Various Maximum Stresses.

Then will come a range of conditions over which single-core ungraded cables will be used, after which the simplicity of the single wall of dielectric material will have to be sacrificed. The relations of working pressure and maximum stress which determine this latter stage are well indicated in Fig. 61, originally given in the author's Paper on "Cables." The diameter limit line is arbitrarily drawn at a diameter over dielectric of three inches, while the stress limit line is approximately determined by dielectric loss considerations, and in course of further improvement in dielectrics may possibly be removable to the right.

For the present considerations, the two left-hand areas are of interest, the upper representing conditions where grading is imperative, and the lower, where it is not essential.

The necessity of separating or lightly insulating the sheaths of such single-core cables in order to prevent heavy circulating currents flowing therein was tentatively discussed in connection with the Paper.

Considerations of this kind were extensively considered by Clark and Shanklin in their 1919 Paper (*l.c.*, *ante*). After examining the character and magnitude of the induced effects, the Authors closely considered the pros and cons of the following alternatives :—

(*a*) Short-circuiting the lead sheaths.

(*b*) Bonding them to earth through resistances.

(*c*) Breaking their continuity and bonding the sections to a neutral ground wire.

(In the foregoing cases the sheaths are earthed at each end as in ordinary 3-core cable practice.)

(*d*) Insulating the sheaths.

The advantage of a comparatively low frequency is well brought out in the cases considered by the authors, it being apparently preferable to short-circuit the sheaths when the frequency was 25 cycles, while at 60 cycles it appeared desirable to break their continuity and bond them to earth at intervals. In the latter case it was shown to be slightly preferable (from the induced sheath-voltage point of view) to break continuity and earth at every manhole (spaced 500 feet apart) rather than to break at every second manhole and bond at the intermediate one, the voltage across the break being thereby halved, although the voltage between sheaths or from sheath to ground would be the same in each case.

In considering (*b*) these authors draw conclusions opposed to bonding to earth through resistances, largely on account of unreliability. They point out, however, that as the induced sheath voltage is proportional to frequency, the conditions tend to be favourable to directly earthing them when the frequency is low.

The advantage of this over a multiplicity of breaks in the sheath and bond connections is apparent, especially when the extreme importance of efficient maintenance of bonds to prevent dangerous conditions arising is considered.

With regard to (*d*), special insulation, apart from that which can be afforded by special duct and manhole arrangements, will possibly not be often required, as the tendency of future practice will probably be for voltages rather than currents to be increased. The British practice of laying cables on the solid system might offer advantages from this point of view, in conjunction with judicious subdividing and earthing of the sections of a feeder line.

In view, however, of the difficulty of keeping ducts dry and solid laying intact, it will probably be found necessary to definitely insulate the lead sheaths by a thin layer of non-hygroscopic (non-fibrous) material—such as vulcanised bitumen—and to adopt definite maintenance precautions to ensure its integrity being kept unimpaired.

STRESS DISTORTION

Having considered the distribution of stresses in dielectrics theoretically, and the limitations of form and conditions of usage influenced thereby, reference may

now be made to the divergence between the theoretical perfection of an isotropic dielectric and the more or less heterogeneous insulating materials used in actual practice, and the effects on stress distribution involved by their lack of homogeneity.

Reference has already been made to this difference in discussing certain proposals which have been made to empiricise the logarithmic law of potential gradient, and the following remarks relate to the degree and character of such discrepancy in the common types of dielectric.

It will probably be appreciated from preceding studies that, as regards degree, the dielectric materials vary from a state of slight and uniform departure from homogeneity, *e.g.*, as in vulcanised rubber or vulcanised bitumen, to a state of coarse heterogeneity, as in the case of a varnished cambric dielectric, in which laminated varnish films are separated, as regards their interior surfaces, by cellular laminæ, and exteriorly, as well as at lateral intervals—represented by the edges of the wound strips—by compound.

As regards variations in the character of the differences, we may visualise vulcanised rubber as a colloidal mass, having materials incorporated in it; some so closely as to be chemically combined or to influence chemical combinations; others, although amorphous, closely held by physical attraction; and yet others of crystalloid form which are physically repelled. With this we may contrast impregnated paper as an irregularly cellular mass of fibres, having the spaces within its felted structure filled with oil, but containing voids of microscopic order in the walls of the cells, *i.e.* the canals in the fibres themselves, which, because of the relatively enormous capillary forces to be overcome, cannot be effectively filled by any ordinary means.

Bearing in mind that any departure from the ideal isotropic character must entail some degree of distortion in the distribution of electric stress, it will be of interest to note the characteristics of each type of cable dielectric in this regard. Foreign substances, of accidental origin, will be excluded from our consideration. A symmetrical electrostatic field, as in a single-core or concentric cable, will be assumed, the tangential type of distortion which occurs at the boundaries of insulated cores in the rotating field of a polyphase cable having already been considered (see p. 218).

To take the case of an impregnated paper dielectric we have as the chief factors in its heterogeneity, (1) free compound, (2) occluded air or gas films or bubbles.

With regard to (1), free compound is distributed (*a*) between the surfaces of successive layers of paper, (*b*) along spiral paths constituted by the slight gaps between edges of convolutions of paper strip in each layer, *i.e.* a "thread" of rectangular section having a thickness equal to that of one paper and a width corresponding to the gap between adjacent edges of the convolutions.

Where the direction of lapping is reversed in the course of building up the wall of dielectric (an early custom which has not quite disappeared) the thread of compound will be expanded into diamond-shaped lumps of the thickness of two papers, where the gaps between convolutions in successive layers cross. It will be readily seen that where thin papers, say, four mils in thickness, are used instead

of the ordinary six-mil papers—a not infrequent specification—an increased number of these compound threads for a given volume of insulation will be entailed.

With regard to (2), occluded air and gas may exist at any point in the wall of dielectric. In the case of an ordinary rubber dielectric, composed of a layer of pure rubber next to the conductor and two succeeding layers of vulcanised rubber, an alteration in the potential gradient may occur at the boundary between either of these components.

It may be noted that the order of arrangement of these layers constitutes inverse grading for voltage, although, as pointed out elsewhere (see p. 174), the arrangement may have been originally designed correctly for insulation resistance grading.

In any given layer of rubber there is a certain degree of approach to homogeneity, which varies with the fineness of the powders incorporated therein, but which is, however, invariably interrupted by crystalloid substances such as free sulphur, paraffin wax, etc., which, as mentioned on p. 95, tend to crystallise subsequently to the vulcanising process, and to migrate to the surfaces of the rubber dielectric.

Vulcanised bitumen is liable to contain occluded gas as a product from the vulcanising reaction, as can sometimes be seen from microscopic examination of thin sections. It can largely be expelled by efficient mastication preparatory to its application to the conductor.

In the case of varnished cambric, the laminated, and at the same time cellular structure has already been noted. The varnish films, apart from not preventing moisture being present in the fabric, also militate against its subsequent expulsion.

The films of compound between the surfaces and the "spiral threads" of compound between the edges of convolutions are comparable with those referred to in the case of impregnated paper. There is a decided probability of moisture and air being trapped in the cellular portion of the laminæ.

EFFECTS OF STRESS DISTORTION

Having visualised the structural imperfections or departures from homogeneity which may interfere with the distribution of the electric stress in cable dielectrics, the effects consequent on this distortion may now be considered. For this purpose, the impregnated paper type may be regarded as sufficiently representative, being, moreover, the only one to which advanced conditions of stress apply in practice.

From the foregoing picture of the composite structure represented in a commercial paper dielectric, and from the earlier description of the conceptions, theories, and work of various investigators on the properties of dielectrics (pp. 191 *et seq.*), it will be clear that these stress distortion effects are dependent on similar considerations to those which apply to stratified dielectrics or to combinations of elementary condensers and/or resistances.

In the present case, the combinations of elements vary between :—

(*a*) Compound and paper (components of impregnated paper).
(*b*) Free compound and impregnated paper.
(*c*) Air, free compound, and impregnated paper.

The local potential drops consequent upon variations in relative resistivities and specific capacities of these combinations, and the resultant residual charges, determine the degree of distortion of stress paths, or deflection of the lines of electric force. The paths for dissipation of the heat produced will be correspondingly irregular, and it will, therefore, readily be seen that if the frequency of occurrence of the combinations above mentioned is low and varied in value—for example, if the air component in (*c*) is large and not uniformly distributed—there will be a tendency to the creation of hot spots and local cumulative heating. In other words, there will be heating due to the distortion of the stress paths, which may be augmented by the loss due to ionisation effects ; while the dissipation of the local heat may be (also locally) hampered by the low thermal conductivity of the air space which largely gave rise to it.

On the other hand, if what may be called the uniformity of heterogeneity is sufficiently good—in other words, if the frequency of variation of its heterogeneous constitution is high—these localised effects will be minimised, and the heat effects may conceivably be uniform. In other words, the hot spots will be so frequent that they will be indistinguishable as such.

Since heterogeneity cannot be avoided it would appear that the nearest approach to homogeneity will be to, firstly, reduce the free components of the above-mentioned combinations to a minimum, and, secondly, to ensure their uniform distribution.

Given uniform impregnation of the dielectric, it is quite possible to have a comparatively large amount of air occluded in it, and yet to avoid the production of hot spots, because under these conditions the distribution of the air is necessarily fairly uniform. Such a cable would not, of course, be suitable for high-voltage working, because its critical ionisation stress—as will be presently seen—would be low, and its losses above that point very heavy ; although at lower stresses than the critical range its power factor will be lower than that of a dielectric containing much less air.

This general relation of the heterogeneity factors leads to the next view of the matter, which is, that while the presence of free compound is a necessity the elimination of free air is wholly desirable in high-voltage dielectrics, and becomes more and more essential as electric stress conditions are advanced.

Ionisation of occluded air has been briefly referred to in connection with dielectric losses, when considering the properties of dielectrics (p. 193), and as, by general consensus of opinion, it is one of the most important factors in the whole matter of high voltage dielectrics, the present juncture would appear opportune for its consideration in some detail.

As noted in Table XIII (p. 186), the specific inductive capacity of impreg-

nated paper is, of the order of three to four times that of air, and therefore the potential gradient in a bubble or thick film of air, occluded in an impregnated paper dielectric, will be three or four times that in the surrounding medium. Its dielectric strength at normal temperature and pressure is, however, so low that it may become ionised at a much lower stress than would have any effect on the surrounding medium.

It will be necessary, in order to focus ideas on this point, to make a brief reference to the dielectric properties of air, so far as they bear on the conditions under which it may exist in a cable dielectric.

A great deal of valuable work bearing on the dielectric strength, conduction through, and ionisation of air and gases has been carried out in this country by J. J. Thomson,* J. S. Townsend,† E. H. Warner,‡ W. S. Harris § and others.

In America, following the pioneer work of J. B. Whitehead,|| F. W. Peek ¶ has very deeply investigated corona effects; Harris J. Ryan ** and F. Dubsky †† have studied the dielectric strength of air films, the former between conductors and the latter between solid insulators.

G. B. Shanklin and J. J. Matson,‡‡ and J. E. Schrader §§ in America, and H. M. Höchstädter (*l.c., ante*) and C. F. Proos (*l.c., ante*) in Europe have made valuable contributions to our practical knowledge of the effects which may occur under the conditions of occlusion of air and gases in paper dielectrics.

A broad general conception of the dielectric properties of air bearing on the matter of ionisation is that when its critical stress is exceeded (Peek determined it as 21 K.V./cm. effective with a pure sine wave), corona formation ensues. In the case of a bare circular conductor, corona starts when this stress is reached at a slight distance outside the surface of the conductor. Peek has shown that this distance, which he calls the "energy distance," is a function of the conductor radius r, and is equal to $0{\cdot}301\sqrt{r}$ cm. The dielectric strength of air under these conditions is therefore :—

$$S_{max.} = 21\left(1+\frac{0{\cdot}301}{\sqrt{r}}\right) \text{K.V.}/\text{cm.}$$

subject, of course, to other correction factors for air density, character of conductor surface, etc.

It may be noted in passing that Peek has shown that the mechanism of break-

* J. J. Thomson, *Conduction of Electricity through Gases.* Cambridge Press, 1906.

† J. S. Townsend, *Electricity in Gases.* Oxford Press, 1915.

‡ E. H. Warner, "Ionisation Pressure." *Phys. Review*, vol. 8, 1916.

§ W. S. Harris, *Phil. Trans. Royal Society*, 1834.

|| J. B. Whitehead, "Dielectric Strength of Air." *Trans. A.I.E.E.*, vol. xxix. (2), 1910.

¶ F. W. Peek, junr., "Law of Corona and Dielectric Strength of Air." *Trans. A.I.E.E.*, 1913, vol. xxxii., No. 2.

** H. J. Ryan, *Trans. A.I.E.E.*, vol. xxx. part 1.

†† F. Dubský, "The Dielectric Strength of Air Films," etc. *Proc. A.I.E.E.*, 1919, vol. xxxviii., No. 2.

‡‡ Shanklin and Matson, *l.c., ante.*

§§ Schrader, "Corona in Air Spaces in a Dielectric." *J.A.I.E.E.*, vol. xli., No. 9, 1922.

down of oils under electric stress also follows ionic theory, and similar corona phenomena occur. The " energy distance " in the case of transformer oils having a breakdown strength of 25·5 K.V. effective is found to be about four times that of air ($1{\cdot}2\sqrt{r}$), indicating that ionic saturation requires a much larger number of collisions.

Ionic theory has not been proved to apply to solid dielectrics, although in the usual impregnating compounds it is difficult to demarcate between the liquid and solid states.

Reference has been made on p. 168 to the theory of Malclès, supported by the experimental work of Del Mar and Hanson, regarding the difference in behaviour of petroleum jelly in the liquid and solid states. It is of interest to note that compliance with ionic theory in the case of solid dielectrics would be opposed to the Russell theory.

In the case of an air space in a dielectric, the form and dimensions of the cavity determine the stress value at which ionisation will commence. When this point is reached, the air becomes partially conductive; and as the stress is increased, the free ions travel at increasing speed between the electrodes—in the present case, the walls of the gas pocket—until, at a sufficient velocity, they ionise, by collision, other molecules of air which lie in their path.

When these conditions are sufficiently advanced, or in other words, when energy is being supplied and absorbed by the action described, at a sufficient rate, disruptive discharge will occur through the gas space.

It will be observed that both chemical and thermal effects may result, the former following the production of ozone, and the latter the energy absorption. It will also be apparent, however, that the size, proportions, and frequency of occurrence of the air or gas cavities and their position in the electrostatic field will determine the degree of deterioration which these effects will occasion.

With regard to the application of the results obtained by the above-mentioned investigators to the cable dielectric case, Dubsky's data is of primary importance, because the air and gas occlusions in an impregnated paper dielectric occur in the form of films, which under conditions of handling the cable or of temperature cycles in operating it, may be changed in dimensions. He found that the dielectric strength of air films enclosed between insulators is practically the same as between conductors, and that the commencement of visible corona phenomena (the criterion of his tests) follows the same law with regard to temperature and barometric pressure conditions, and thickness of the air film.

Inspection of the curves given in Fig. 62, taken from Dubsky's Paper, shew that although, as the Author points out, the dielectric strength of films of the order of one mil in thickness approximates to that of some ordinary insulating materials, the rate of fall with increase of film thickness is forbiddingly steep, showing that to attain high dielectric efficiency there should be no compromise on the matter of entire elimination of air from high voltage cable dielectrics, especially in view of the liability of change of dimensions of the films, as mentioned above.

Shanklin and Matson's experimental results, regarded very broadly, shewed the importance of reducing gas or air spaces in high-tension cable dielectrics to a

minimum. Their methods showed much ingenuity, but they were singularly unfortunate in the quality of the cables on which they operated, judging from the general order of the results which they obtained, and not less so in some of the deductions they drew therefrom. For example, practical experience was some years in advance of a certain opinion the Authors expressed as a result of their experiments, viz., that "it would appear that 19 or 20 K.V. per cm. should be selected as the maximum allowable working stress in a cable of this type,* assuming, of course, that the cable is compactly made up and in good condition, and further, that the working voltage has approximately a sine wave." The apparent fact that they were unaware that this working stress had been exceeded in a large number of cases, both in Europe and America, for a number of years without sign of trouble, together with one or two other weak points, created a rather bad impression, and tended to rob the Paper of the interest to which in some respects it was entitled.

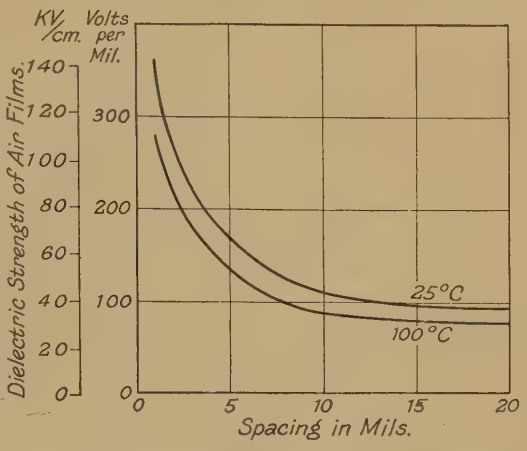

FIG. 62.—DIELECTRIC STRENGTH OF AIR FILMS (DUBSKY).

The low quality of the cables on which the Authors experimented is shewn by the low ionisation points which they found. These were of the order of 22-25 K.V./cm. in cables distinguished as well made, but as low as 12-14 K.V./cm. in cases where large gas spaces were contained in the dielectric.

By ingenious methods based on experimental and calculated data the Authors arrived at measurements of the maximum thickness of gas space, from which it appeared that in the latter case the thickness would be of the order of 18 mils, and in the former (the well-made cables) about one-seventh of that value.

It will, however, be seen by comparing these figures of critical ionisation stress and film thickness with those obtained by Dubsky, that the Authors' values are from 2 to $2\frac{1}{2}$ times as high in the case of the smaller thickness of films, and from 3 to $3\frac{1}{2}$ times in the larger. If this comparison is permissible, it would appear that there is a considerable difference between the dielectric strength of films of air under Dubsky's test conditions, and that of occlusions of air and/or gas as they exist in a cable dielectric. The presence of organic vapour in occluded air would not account for this, as the dielectric strength of such mixtures is usually higher than that of air. The point is of importance, but does not appear to have been since cleared up.

With regard to the manner of occlusion of air and gases, the Authors pointed out that in the ordinary vacuum-pressure method process of impregnating paper

* Described in the Paper as "Single conductor Paper Cable. Filled with Mineral Hydrocarbon Base compound. Lead sheath"—*i.e.* a common American type of paper-insulated cable.

cable a certain amount of impure air remains in the paper lappings when the cable, after vacuum treatment, is flooded with compound; and is driven back by the pressure treatment into the spaces between the lappings, afterwards expanding to atmospheric pressure when the impregnating process is completed, but being ultimately reduced in pressure by reason of the viscosity of the compound preventing equalisation with the atmosphere when cooling, and to some extent by the shrinkage of the compound. * (See Manufacture—Paper Cables, Vol. II.)

The Authors remarked that their test results shewed that the spaces chiefly tend to exist in the neighbourhood of the conductor, where of course the maximum stresses occur, and also laid considerable emphasis on the desirability of using materials of the lowest possible permittivity (specific inductive capacity), pointing out that differences in the permittivities of the gas and the solid material make the stress on the former considerably higher.

They stated that they found ionisation to be independent of frequency over the ordinary range employed in power supply (25 to 60 cycles).

As a result of finding a tendency for ionisation effects to disappear at high temperatures (they were stated to be occasionally absent at 70° C.), the Authors suggested that this might be due to a general readjustment whereby, owing to the expansion of the component parts of the dielectric mass, the layers of paper are pressed closer together, causing the air-bubbles to expand laterally and become reduced in thickness to an extent which renders the stress across them insufficient to produce ionisation.

In this connection they further suggested that similar differences which they found between new and old cables might be accountable for by a readjustment of this kind being made permanent by resetting of the impregnating compound after the softening due to heating in work.

Obviously, this cannot be taken to indicate an inherent property of impregnated paper dielectrics, as a great deal would depend on the relation between the physical properties of the impregnating compound and the temperature conditions to which it is exposed.

Referring back to the viscosity curves of impregnating compounds, Fig. 31, p. 170, the effect in question would appear more likely to occur in compounds such as curve A relates to, than in the case of those used in the vacuum-pressure process of paper-cable impregnation, B, C, D, etc.

The author has had under observation for a long time a cable which was made specially, for comparative purposes, with a large amount of contained air. Among other comparisons for which it has been used, is one bearing on the point in question, with the result illustrated along with several other points in Fig. 63. This shews that after a rest period of eleven months, some such settling effect as suggested by Shanklin and Matson has occurred. The power factor/voltage curve is appreciably lower than at the beginning of the rest period, largely due to the critical ionisation point having been elevated by the presumed readjustment effects. On making corresponding power factor measurements when reducing the applied test voltage, however,

* As is well known, the effect of reducing the pressure is to lower the breakdown gradient across an air or gas space.

it becomes evident that the change is not a permanent one, the tendency to return to original values being quite marked. The increase in power-factor values on the downward curve is apparently due to advance in the ionisation conditions which have commenced during the first part of the test.

It is hardly conceivable that expansion of the air films is also represented; if so, it can only have been brought about by local heating in the air cavities themselves, the time occupied in the whole of the test being only ten minutes. Further, in this event, internal pressure would occur, tending to check the ionisation.

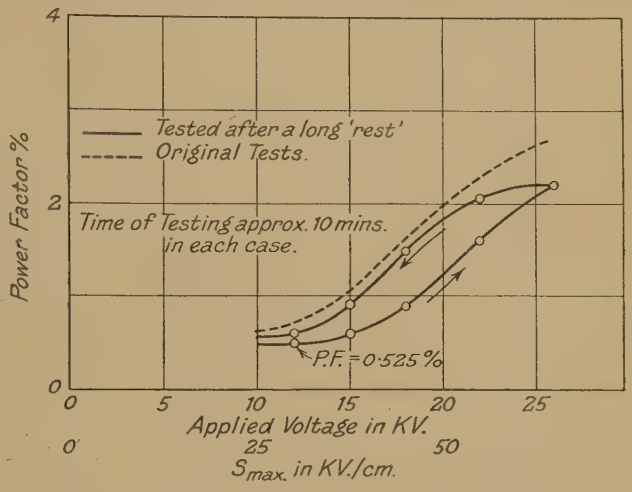

FIG. 63.—VARIATION OF POWER FACTOR WITH APPLIED VOLTAGE.

Other points illustrated by these curves are: (*a*) That low-power factor at voltages below the ionisation point is no criterion of excellence, because under certain conditions (simple trapping of air in perfectly impregnated material) an abnormally low value may be obtained in a bad cable. (*b*) That testing procedure requires to be standardised, because results are only comparable under constant conditions of determination. (*c*) That in connection with standardisation of methods of procedure particular attention should be paid to the time element in determining variation of loss with voltage.

With regard to (*a*), Schrader (*l.c.*, *ante*) obtained similar results from experiments on sheets of impregnated material between which were interposed definite air films.

In addition to finding a definite increase of power factor at the commencement of ionisation he noted that a thicker air space with a given thickness of dielectric shewed more abrupt change of power factor, and that this occurred at a lower potential gradient. He also found that after reaching a maximum value of power factor, indicating saturation of ionisation, the power factor decreased, this apparently indicating the point where the ionised air begins to act as a conductor between the remaining parts of the dielectric, whereas, previously it had acted as an air condenser in series with them.

Under this condition the charging current will increase more than proportionately to the voltage, and this will decrease the power factor if the losses do not rise as fast as the product of the voltage and charging current.

It was also shown that at stresses below the ionisation stress, the power factor of dielectrics enclosing large air films was *lower* than that of dielectrics with thin air films.

Del Mar and Hanson also stated in their 1924 paper * that given enough moisture in an impregnated paper dielectric (due to inadequate drying and lack of impregnation) to allow appreciable leakage, the power factor is constant over a wide range of voltage. This is in accord with the leakage theory, as the leakage current will increase with voltage over the whole range.

With regard to (*b*) and (*c*) the desirability of standardising this procedure was strongly urged by Proos (*l.c.*, *ante*). As shown in Fig. 41, the time effect was very appreciable in the case cited by Proos, but under constant conditions, even the condensed form in which the author uses this test has been found very instructive.

Proos does not appear to utilise the time effect directly in his test scheme which, according to his proposals of November 1923, covered (1) the determination of the voltage characteristic at normal temperature and frequency, the criterion in this case being departure from the square law which is specified not to occur below a certain multiple of the rated voltage of a cable. (2) A repetition of (1), after raising the temperature of the conductor by means of current to 40° C. It is specified that the values obtained under this condition should not be more than double those obtained under test (1), the actual values not to exceed 0·001 (watts/K.V.^{2}) per metre. (3) A further repetition of (1), after allowing the cable to cool down to between 10° and 15° C. The proportionality of the losses to the square of the pressure to be constant up to within a certain specified limit (about 10 per cent.) of the corresponding voltage specified under (1).

It may be generally concluded from a study of Fig. 63, that the simple specification of a power factor value may be misleading, and that considering the preponderating influence of the ionisation of occluded air and gases in the sum-total of dielectric losses, ionisation data is more informative than a power-factor value.

As noted in referring to Proos' voltage characteristic curve (Fig. 40) this investigator traced ionisation effects up to a state of approximate saturation, represented by the third portion of his curve, which was still sloping slightly.

Schrader went further,† and found that a decrease in the power factor ultimately occurred. His conception of the whole process was that as the potential gradient was raised, the free ions in the air space, though few in number at the start, acquired sufficient velocity to ionise other molecules in their path by collision, and that this continued until corona formation took place. At this point a large increase in the losses was observed, the relation being such as to increase the power factor. He further found that as the potential gradient was raised still further, the major portion of the air was completely ionised, until a condition was reached when an increase of potential gradient did not produce a corresponding increase of loss, and consequently the power factor decreased.

It is a moot point as to what eventually happens to the ionised air. Shanklin and Matson found that ionisation effects disappeared in course of time, and this appears likely to have some foundation, in view of the irreversible chemical actions which are concerned.

* "High Voltage Impregnated Paper Cables," *Jour. A.I.E.E.*, vol. xliii., 1924, p. 950.
† See preceding page.

The fact has already been referred to (pp. 197 and 239) that cables in which the working stresses exceed the ionisation stresses have been in successful operation in various parts of the world for a number of years.

Beyond all doubt these cables were less well made than similar cable of more recent manufacture, and contained air and gas bubbles and films in much greater profusion. Yet they do not appear to have given proportionally more trouble in consequence, or, to regard the matter conversely, the reduction of the proportion of occluded air and gas—and probably also the size of the unit bubbles or films—as evidenced by the very considerable general reduction of dielectric losses, has not effected proportional improvement in operating results, nor eliminated the symptoms of ionisation effects which, at least so far as appearances go, are stated by those with intimate experience of them to be even more apparent. In fact, the much discussed tree formation appearances (see p. 197) do not seem to have been at all noticeable in the old cables, although such failures as occurred were usually diagnosed as being due to cumulative heating, consequent on high dielectric loss.

Assuming the correctness of these premises :—

(*a*)* That the cause of failure in both old and new cables has been the ionisation of occluded air and gases ;

(*b*) That there has been a substantial reduction in the proportion of these occlusions in the newer cables ;

(*c*) That improvement as regards freedom from failure in the newer cables has not been proportional to the reduction (*b*),

the logical deduction would appear to be that the difference in the final effects must be due to difference in the form, dimensions, and distribution of the occlusions.

It is fair to assume with regard to the thickness of the air films that they are generally thinner in the more recent cables than in the earlier ones. (The author has shown comparisons of this kind by means of X-rays.) Dubsky's dielectric strength tests on air films (see Fig. 62, p. 239) show that for films of small thickness the values rise rapidly with diminishing thickness. With regard to the ionisation of them, Schrader deduces from his work that complete ionisation is more readily brought about in a thick air space than in a thin one, because the rate of multiplication of free ions by collision is proportional to the distance they travel in the air space ; and that in thin spaces the free ions do not attain sufficient velocity to produce other ions in their path. Hence a higher potential gradient, corresponding to the higher velocity of the ions, is necessary to arrive at the stage of corona formation, mentioned in the above reference to Schrader's work. Presumably the tree-pattern formation is brought about at or beyond the corona

* Dunsheath (*Electrician*, vol. xciv., 1925) does not appear to connect the tree-formation phenomenon with the ionisation of occluded air in the dielectric, but simply refers to it as progressive deterioration by burning as distinct from failure by reason of the applied stress being beyond the dielectric strength of the material.

Note.—Dunsheath's views were elaborated in his paper on "Dielectric Problems in High Voltage Cables," read before the I.E.E. on 5th November 1925, at which date the final proofs of this volume had been passed to the printer.

stage, so that the amount of energy per unit volume of the dielectric—which is the key of the situation in all questions of mechanism of breakdown—may be conceivably even greater in the case of a thin film than a thicker one. If this is so, there is obviously a range of critical thickness of film for given conditions of potential gradient; and, to pursue the suggestion to its conclusion, avoidance of the critical dimensions of film in the newer cable (where the proportion of occlusions to the total volume of dielectric is comparatively low), and/or of conditions of cumulative heating in the older cable (where the films, though of larger average dimensions, occur more frequently), constitute the conditions of escape from jeopardy.

Del Mar and Hanson, in their 1924 Paper (*l.c.*, *ante*) make an interesting suggestion relating to the tree formation, which is based on visual observations of the combined effect of surface leakage through the air films, and ionisation of the air. Their explanation is to the effect that under the influence of ionisation conditions in the film, this surface leakage—which previously obeyed Ohm's law—takes on a new volt/ampere characteristic, dependent on the degree of ionic saturation.

The ionisation of the air causes the leakage current to flow as streamer discharges, with a liberation of energy corresponding to the degree of ionisation. Failure results from the charring of the insulation either along the path or at the ends of the streamer.

Incidentally, the Authors confirm the writer's impression that the older cables showed no sign of the charred tree pattern, but advance the explanation that probably the low resistivity of the oil kept the leakage in the stage of ohmic conduction, and thus restrained the local liberation of energy. The author knows of no ground for the supposition that the resistivity of the oil has been varied, and it would seem unlikely that such variation would have been made independently and coincidently in America, Great Britain, and the Continent. On the other hand, variation of the dimensions of air films could easily result, independently of materials of any kind, from the efforts which all cable-makers have been putting forth to eliminate or minimise the occlusion of air and gases in their dielectrics.

It should perhaps be here mentioned that the suggested explanation put forward by the author is purely speculative, and based on the circumstantial evidence in connection with the subject. No experimental work has been done in connection therewith, largely because his own process of manufacturing high voltage cables, elsewhere referred to and described, obviates the whole risk of the trouble by assembling the perfectly prepared insulating material on the conductor out of contact with air, *i.e.* under the surface of molten compound.* This process is referred to in various parts of this volume as the "new" method.† This description really only applies to the assembly of the dielectric and conductor, or of laid-up cores and overall insulation; the method of impregnating the paper prior to its application to the conductor was introduced by the author in 1897, and has been solely used by his firm in the interim.

* Beaver, Pat. No. 182510/21, etc. † Known as the "precise paper lapping" method.

Figs. 64 and 65 shew comparative loss/stress and loss/temperature curves for identical cables made by old and new methods.

Detailed reference to the manufacturing points concerned in the new method, *i.e.* the precise assembly of the dielectric under air-free conditions, is made in Volume II.

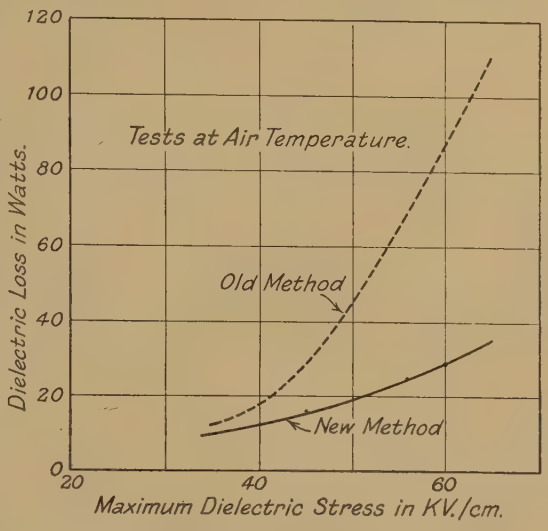

FIG. 64.—VARIATION OF DIELECTRIC LOSS WITH DIELECTRIC STRESS.

Reverting to the general aspect of dielectric losses, it will be amply evident that all the imperfections or heterogeneities already referred to as causing distortion of the electrostatic field will lead to more or less acute local potential gradients and corresponding loss in the dielectric, which if they are sufficiently susceptible or unstable in character, or marked in degree, will lead to deterioration and ultimate failure of the dielectric. Theoretically it is possible to conceive, according to Clerk Maxwell's theory of stratified or composite dielectrics referred to on p. 191, that if we had a dielectric composed of two elements having suitable values of resistivity and specific inductive capacity, and that physically they existed in the dielectric in the state referred to on p. 236, as uniformly heterogeneous, it might constitute a dielectric having a minimum loss.

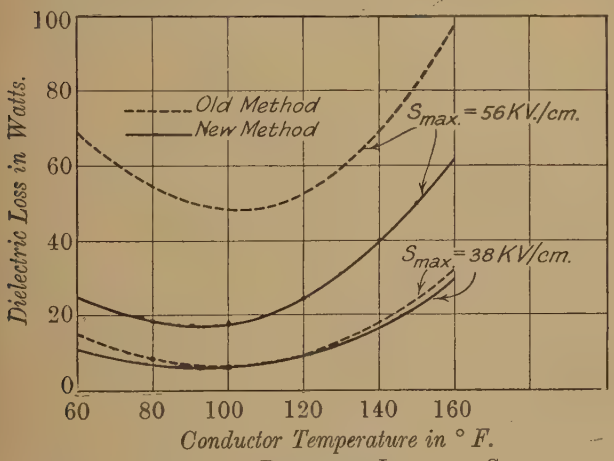

FIG. 65.—VARIATION OF DIELECTRIC LOSS WITH CONDUCTOR TEMPERATURE.

In practice, owing to the complexity of the available substances, the utmost that can be done in the present state of our knowledge is to select, combine, and build up materials to the best advantage, so as to secure maximum permanence and electrical efficiency. This should include the choice of materials which in their combined and perfectly prepared form afford the greatest dielectric strength and minimum dielectric loss compatible with the physical requirements of working conditions, and the assembly of such prepared material under conditions of

precision of application and avoidance of imperfections as may be practically possible.

A substantial weight of opinion, both in Europe and America, has somewhat intangibly, during the past few years, been in favour of wood-pulp paper for use on high-voltage cables.

Figs. 66, 67, and 68, shew results of comparative tests of variation of dielectric loss with voltage, temperature, and time respectively, on single cables insulated with sulphate process wood pulp paper and manilla paper respectively. The insulation was applied to these cables under identical conditions by the new precise method which gives excellent facilities for close and direct comparison of materials embodied in cable form.

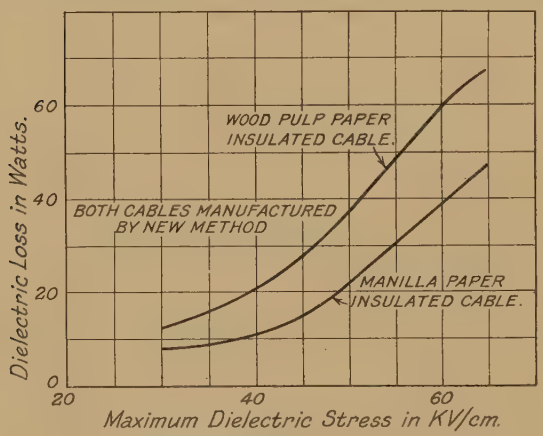

Fig. 66.—Variation of Dielectric Loss with Dielectric Stress.

It will be observed that manilla paper consistently gives superior results under each condition of test.

Elsewhere in this work the author has stated that the net result of comparative tests in various directions, as to the merits of papers of different composition, have never been in favour of wood-pulp as compared with manilla paper.

With reference to impregnating materials, there has for many years existed in America a strong and widespread objection to the use of resin, particularly in connection with high-voltage cab'es. The author believes that this adverse attitude towards an extremely useful and suitable material had its origin in a false deduction by an American investigator in the course of a research on cables. As a result, cables in which resin has entered the composition of the impregnating compound have been commonly known under the stigma of " high-loss " cables.

The wave of opinion was reflected to Europe, but with very little deterrent effect on its emp'oyment, except that, comparatively recently, in the endeavour to secure low power factor figures, some tendency has been noticeable to sacrifice the valuable physical (and, in other directions, electrical) properties which this material can give to a compound which is well designed to attain a maximum average of all desirable properties. The few preceding pages will be a sufficient commentary on this matter, if only from the point of view of the preponderance of other factors.

The subject appears to have recently come under review in America, Del Mar and Hanson devoting an appendix in their 1924 Paper to its consideration. They first state that American manufacturers abandoned resin on account of its chemical instability at the temperatures at which American cables are operated,

and that the lower operating temperatures employed in Europe permit its use there.

This statement is quite void of foundation. The working temperature referred to does not exceed 85° C., whereas resin shows no instability at twice that temperature. In fact, large tanks of resinous compound in continuous use at about 150-160° C., are common objects in a cable factory.

The Authors admit the physical advantages of resinous compounds, and also while showing that 10-15 per cent. of resin reduces the resistivity and increases the power factor of petrolatum, state that increasing the proportion raises the resistivity again, and that a 50 per cent. addition gives a low power factor. The latter percentage much more nearly represents ordinary practice, so that the Authors hardly succeeded in showing good reason for the abandonment of resin in American practice. The authors hint at a return to its employment under modified conditions at a later date.

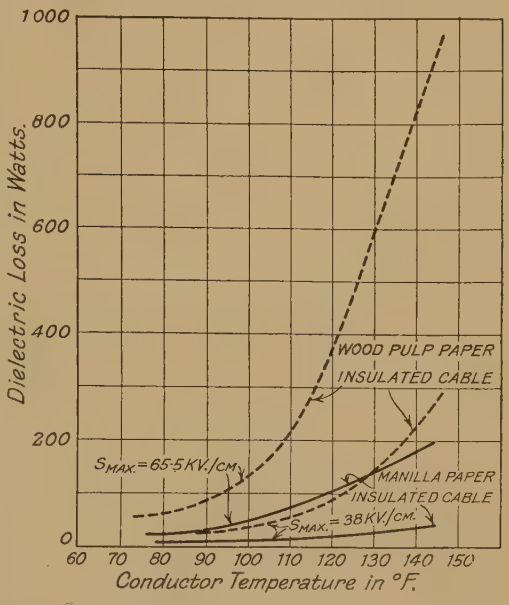

Fig. 67.—Variation of Dielectric Loss with Conductor Temperature.

As stated elsewhere in this work, page 25, the author has found improvement regarding dielectric loss to depend much more on construction and assembly than on variation of impregnating materials.

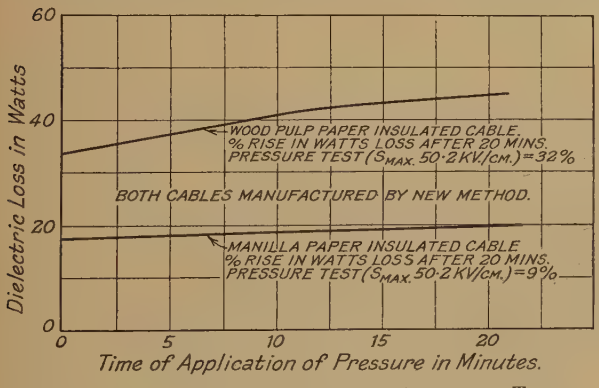
Dielectric Loss in Watts
60
40
20
0
0 5 10 15 20
Time of Application of Pressure in Minutes.
WOOD PULP PAPER INSULATED CABLE. % RISE IN WATTS LOSS AFTER 20 MINS. PRESSURE TEST (SMAX. 50·2 KV./CM.)=32%
BOTH CABLES MANUFACTURED BY NEW METHOD.
MANILLA PAPER INSULATED CABLE. % RISE IN WATTS LOSS AFTER 20 MINS. PRESSURE TEST (SMAX. 50·2 KV/CM.)=9%

Fig. 68.—Variation of Dielectric Loss with Time.

Having now dealt with the most important factors bearing on design requirements and manufacturing desiderata from the voltage aspect, there remains a further matter of not less vital importance, and at least equal complexity, to be considered from the same point of view, *i.e.* the voltage conditions of usage.

About the beginning of the present century, when electric power transmission at 6600 volts was coming into vogue, so little was known and so much was feared regarding the possibility of setting up voltage surges, and the risk of resultant damage to insulation, that

charging devices (usually of the water-resistance type) were frequently employed in switching cables on to high-tension busbars.

At the present time, thanks to the knowledge gained by switchgear makers and cable manufacturers through oscillographic investigations, etc., the necessity for such devices does not arise at any working pressure for which insulated cables are made.

Broadly speaking, however, the principle insisted upon by the author regarding conformity between dielectric stress conditions and cable manufacturing matters has its parallel with regard to the care of cables in operation.

At working pressures of 20 K.V. and upward, failures have occurred which have clearly not been due to either extraneous (physical or mechanical) causes, nor to any internal imperfection in materials or workmanship. The most exhaustive tests in all directions have failed to provide any positive evidence bearing on causes of failure. Breakdown tests on lengths contiguous to the point of failure, power-factor tests on complete lengths, separate tests on component parts arranged in different ways, visual and microscopic examination, chemical analysis, etc., have only produced negative evidence.

Voltage wave forms have been found impeccable, even under conditions of switching cables on load in and out ; all kinds of ramifications of working conditions have been watched with oscillographs, without positive evidence bearing on faulty conditions resulting. In fact, the negative proofs have been so consistent as to constitute positive evidence that the cause of breakdowns was not inherent in, nor related to anything abnormal about the cable.

The general feeling emerged from all this negative evidence, though lacking proof, or even tangible support, that some surge or "transient" effect was the only feasible explanation. A great deal more experience has been gained in America on this subject than in this country, because of the much more extensive scale on which high-voltage transmission systems are laid out, and the less restricted conditions under which they are operated. Study of American experience, however, only furnished information which could be used in speculative fashion in connection with the foregoing evidence, but the tentative conclusion which appeared to be indicated, was that the trouble was due to some obscure transient effect acting in conjunction with dielectric phenomena.

The second factor concerned in this suggestion is less speculative in character than the first, because the characteristics of electrification, polarisation, and residual charge in a dielectric, elucidated by Clerk Maxwell more than fifty years ago, constitute a true (though exceptionally slow) electrical transient.

This was pointed out by Steinmetz in his 1924 Paper,* in which he showed that this phenomenon of the electrification of a cable is the result of and is explained by the energy adjustment of a system with constant values of resistance, inductance, and capacity, *i.e.* it is no different from the starting or stopping transient of the ordinary circuit except that it is "a thousand times slower," due to the fact that the resistance in the circuit is the leakage resistance of the cable dielectric, and therefore extremely high.

* See p. 193.

He took the case of a cable dielectric consisting of two or more materials, having different resistivities or different specific capacities or both, and shewed that at the moment of voltage application, the voltage distributes between the component materials in proportion to their specific capacities, gradually changing to a distribution proportional to their resistivities, and that electrostatic charges builded up in the interior of the dielectric at the boundaries of the component materials.

In the discharge, the reverse happens, and the internal charges slowly disappear by conduction through the dielectric. The distribution of dielectric stress between the component dielectrics changes, and this may give a different dielectric strength for alternating and direct voltages.

With Steinmetz' conception in mind, we may next picture the average effect of charging up this composite dielectric by the application of an alternating voltage at an ordinary commercial frequency of 25 to 60 cycles per second. In this charging condition the continuous supply of energy equals the energy dissipation, and the operation may therefore be regarded as the application of a continuous oscillation—an extremely low-frequency oscillation, just as the electrification of the dielectric was regarded as a slow transient—to the dielectric. (Incidentally, at this stage it needs little imagination to understand the origin of the old expression, "dielectric viscosity," used by early investigators of dielectric phenomena, in explanation of residual charge.)

If we now imagine the superposition of a transient on the above set of conditions —it matters little for the purpose of the picture whether it be a cumulative oscillation such as may be due to the "hunting" of synchronous machines, a steep-fronted wave, or a train of waves, or what the wave-form is like –and if we further assume the coarsely heterogeneous structure of dielectric to which reference has previously been made, and if, still further, we bear in mind the probability of the simultaneous existence of high-frequency continuous oscillations due to ionisation in air cavities, little argument is needed in favour of homogeneity of dielectric on the one hand, or protection from transient effects on the other.

The latter point has, of course, received attention in a general way, but it would seem likely that sufficient distinction has not been made between the requirements in the case of high-power transients such as lightning discharges, and those which continuously dissipate oscillating energy from cable dielectrics.

The former are outside the scope of this work, but it may be of interest to note that, so long ago as 1905 (*Jour. I.E.E.* vol. 36, p. 66) Mr W. H. Patchell described a special construction of spark gap of the horn type, which he had used with considerable success at the City of London Works of the Charing Cross Supply Company, in which the horns, one made of copper and the other of carbon, were contained in a glass enclosure.

The chimney action due to this enclosure facilitated the travelling of the spark upwards in the gap between the horns. A liquid resistance was used in series with the spark gap.

This apparatus was simply a refined form lightning arrester, but it was found to be capable of fairly accurate calibration and delicate adjustment.

Mr Patchell used this apparatus in conjunction with detective devices and obtained many interesting results therefrom, the outstanding feature of which was the frequency of the indications it gave of pressure rises on the network.

More recently Mr Partridge described in the *Electrical Review*, 20th June, 1924, the method which he had used for somewhat similar purposes on the mains of the London Electric Supply Company. The apparatus in this case consisted of a Wurtz Arrester which, as is well known, consists of a number of spark gaps between small metal cylinders connected in series with a set of current limiting non-inductive resistances of the carbon-powder type. The arrangement is shewn in Fig. 69, reproduced from Mr Partridge's article above referred to.

The last two metal cylinders in the earth side of the Wurtz arrester were so arranged as to allow a strip of paper to travel between them in the ordinary way

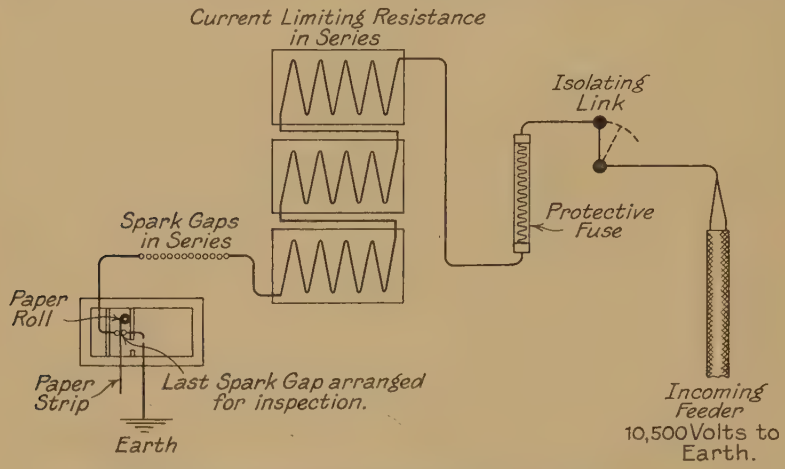

Fig. 69.—Diagram shewing Arrangement of Surge Protection Apparatus set to Operate at 14,000 Volts (R.M.S.).

employed on a recording instrument, the record in this case being punctures caused by sparks passing to earth through the arrester.

The apparatus was applied to four single-phase concentric trunk mains, feeding four sub-stations at a working pressure of 10,500 volts at 85 cycles. The lengths of these feeders, according to a diagram given in Mr Partridge's article, were of the order of 7·5 miles in the case of Feeders 1 and 2, and 6·5 miles in the case of Nos. 3 and 4, about 28 miles in all.

The same diagram indicates that feeders 2 and 4 included lengths of the historical Ferranti mains,* the proportion being nearly 50 per cent. of the total length in No. 2, and nearly 43 per cent. in No. 4. Each of these two feeders commenced with about $1\frac{1}{2}$ miles of Ferranti cable, the remainder being at the sub-station end. Nos. 1 and 3 were entirely composed of ordinary concentric cable.

The Wurtz arrester was set to spark over at 14,000 volts, *i.e.* 35 per cent. above

* See p. 23.

normal working pressure, and the extremely interesting and important results obtained from five years' observation, recorded by Mr Partridge, may be summarised as follows :—

1. During this period the number of pressure rises of sufficient magnitude to be recorded by the apparatus was 332.

2. Of these, only 52 (*i.e.* about 18 per cent. of the total) occurred on Nos. 2 and 4 feeders, *i.e.* those containing lengths of Ferranti cable, although all the feeders were exposed to the same operating conditions.

3. The records shew that the pressure rises had in most cases no possible relation to variations in the applied voltage, nor to switching operations.

4. They also shew that pressure rises occurred much more frequently at times of light load than at times of heavy load. It is stated that three times as many rises were recorded between 10 P.M. and 6 A.M. as during the rest of the day.

5. Rises were found to be more frequent during summer than in winter. The records shew that of the 332 discharges registered, 232 occurred during the period of April to September, inclusive, and only 100 during the remainder of the year.

6. Atmospheric effects were shewn to have no connection with the more frequent rises indicated by the records as occurring in summer. One main, disconnected from the system during the whole of the summer of 1923, with only one spark gap (instead of the normal number of twelve), connected between the inner conductor and earth, shewed no rises.

The outstanding value of Mr Partridge's observations lies in the practical demonstration of the fact that elimination of breakdowns due to surges normal to the operation of a cable system may be attained by draining away, as it were, the surplus charges from the cable dielectrics ; and in doing this, secondary effects of breakdown which may be reflected to other parts of the system are also avoided. In the case under review, although no figures are given, mention is made of " frequent breakdowns of mains and transformers " prior to installing the apparatus, and " practically no failures on either the transformers or the mains since the apparatus was installed five years ago."

To view the other extreme, it is naturally disappointing that practically no information has emerged regarding the character or source of the pressure rises ; although it is clear from the foregoing summary of the results that the difficulties in this direction are very great. For example, it will be seen from (1) and (5) that the recorded rises average less than two per week in the summer months, and less than one per week in winter. To detect such infrequent transients by ordinary oscillographic means would be an impracticable proposition.

With regard to (2) Mr Partridge concludes that the reason of the smaller number of recorded rises on the feeders (Nos. 2 and 4) which included lengths of the Ferranti cable, is that the joints therein—which occur at intervals of 20 feet—act as a general leak across the system, and thus prevent pressure rises. Presumably Mr Partridge has definite information as to the insulation resistance of these joints being abnormally low, in which case the deduction would appear to be a justifiable one.

Certain inferences contained in a summary of the article prepared by the Sub-

Committee on Wires and Cables of the A.I.E.E. Standards Committee * are, however, misleading. The abstract states that " the pressures on the 6½ miles of old cable were 52, while those on the 21½ miles of modern cable were 280, *i.e.* 60 per cent. more per mile on the *low loss* cable." Reference to (2) and the preceding data will show that the 52 pressure rises were on feeders 2 and 4 which *included* 50 per cent. and 43 per cent. respectively of the " old " (Ferranti) cable, and not on the 6½ miles of old cable, this obviously not being determinable.

The length of feeder 1 was equal to that of feeder 2, and 3 was approximately equal to 4, and as operating conditions have been stated to be identical, the correct deduction from the evidence would rather be that the effect of the inclusion of the lengths of Ferranti cable was to reduce the number of pressure rises on the feeders containing them.

Further, there is no justification for the inference contained in the expression " low loss " cable. Reference to the brief description of the method of manufacture of the Ferranti cable on p. 23 of this volume will indieate a distinct probability that its dielectric loss is *not higher* than that of the other cable. In any case, without definite data on the point, the matter of dielectric loss should not be obtruded.

With reference to (4) and (5), the evidence tends to indicate that dielectric temperature is not concerned, the two statements being rather cancellatory in this respect. It would therefore appear that the system has been rather susceptible to the setting up of transients under light-load conditions. Possibly (with regard to (5)) summer conditions entail more periods of light load, but no data is given in the article on this point.

It may be remarked that similar apparent light-load susceptibility has been frequently noted in the case of 33 K.V. cables, although, owing to the consistent coincidence of minimum temperature conditions, due to cooling down over the week-end, physical conditions in the dielectric consequent on contraction of the insulating material have been adjudged the immediate cause of failure. This matter is dealt with under " Deterioration and Causes of Failure " in Vol. II.

In the author's opinion, it is not sufficiently appreciated that our knowledge of transient effects is very limited, at least, so far as the more destructive types of oscillations are concerned. We know that resonance effects are generally sufficiently far removed by the average characteristics of power circuits, and experience has shewn that the simple energy adjustment transients which are related to the ordinary operating conditions of networks are not beyond the care of our average factors of safety ; but we know little of transient effects which may be independent of cable characteristics, due for example to the well-known " arcing ground " phenomena.

In view of the complexity of the cable dielectric problems involved by high working voltages, and, concomitantly, enhanced dielectric stresses, the provision of efficient means for the dissipation of oscillating energy which may become superposed thereon would appear to be an absolute necessity.

* Del Mar, " Electric Cables." McGraw-Hill Book Co. Inc. 1924.

CHAPTER XI

SHEATHS

THE term " sheath " has been defined on p. 106 (Protective and Preservative Materials) as " a continuous homogeneous covering of impervious material, applied over an insulated conductor or an assembly of insulated cores."

It will be noted that this definition excludes the use of the term with reference to non-continuous coverings, although it is often used in this connection. For example, " a sheath of armouring wires " is a commonly used expression emanating from early submarine telegraph cable practice.

The primary function of a sheath was also indicated (*ibid.*) as the exclusion of moisture and the general protection of the dielectric against external deteriorating or damaging influences, such as chemical attack or mechanical damage. It may be added that it is further characterised by the method of formation or application, which is almost invariably by extrusion after suitable preparation (see Manufacture, Vol. II.).

Incidentally in the more usual types and forms of cables, it also facilitates the attainment of a circular section, although sheaths can equally well be applied to the flat or " side by side " form of twin or multicore cables.

With regard to the composition of sheathing materials, it was also stated that " sheaths may be composed of metallic or non-metallic materials, the former being almost invariably lead or an alloy thereof, and the latter vulcanised rubber, vulcanised bitumen, or some special material of generally similar character."

Apart from the physical, chemical, and mechanical functions above mentioned, electrical factors also enter into the matter. A metallic sheath, for example, forms a definite " earth " boundary to the dielectric, thereby tending to make dielectric stresses symmetrical in any given cross-section of the cable.

It also functions as an " earth shield " by taking care of leakage currents from the conductors and preventing the charging up of the surroundings when a fault develops. It also acts as an earth-circuit conductor for the conduction of vagrant currents, so that under proper conditions of bonding and earthing it affords protection against electrolytic effects which may tend to be set up by extraneous causes.

Further, in connection with maintenance tests a metallic sheath permits the insulation resistance of a cable dielectric to be measured with a degree of accuracy which is unattainable in the case of a cable with a non-metallic sheath, because the dielectric is definitely bounded by the conductor on the one side and the metal sheath on the other.

The incidental electrical functions of a *non*-metallic sheath are of a different order. The sheath virtually constitutes an additional thickness of dielectric between conductors and earth, and therefore augments the electrical value of the dielectric proper to an extent which depends on the insulating properties which are incidentally possessed by the sheath material.

In comparing the respective electrical functions of the two types of sheath,

it will be appreciated that an armoured non-metallic sheathed cable, such as a wire-armoured vulcanised bitumen-sheathed cable, embraces both sets of conditions.

Lead or alloy sheaths are applicable to all types of insulated cable, and the same remark applies to vulcanised bitumen; but for reasons of practical manufacture, connected with the necessary exposure of the whole cable to the vulcanising temperature, vulcanised rubber sheaths may be generally considered as only applicable to rubber-insulated cables.

Ordinary lead-sheathing practice calls for the use of virgin lead which, as stated under "Materials," p. 110, is commercially obtainable—in the best brands—of 99·98 per cent. purity.

As mentioned under "Protective and Preservative Materials" (p. 114), lead is sometimes alloyed with small percentages of tin or antimony, with the object of imparting a certain degree of stiffness to the sheath; primarily these alloy sheaths were designed for use on "dry core" telephone cables, and latterly they have been used for metal-sheathed insulated wires in connection with surface wiring systems.

Questions of design relate chiefly to the provision of a sheath which is mechanically adequate, and radial thicknesses of lead sheath naturally vary in proportion to diameter. Further reference is made to this point in Vol. II.

Where questions of sheath conductivity arise, as in special concentric systems of wiring, or in mine cables subject to the H.O. Mining Regulations, a value of about one-twelfth of the conductivity of electrolytic copper (as stated under "Materials," p. 113) may be assumed for commercially pure lead.

As in both these instances, however, the conductivity of the outer copper conductor or the wire armour is the predominating factor, and that of the lead sheath supplementary thereto, it is seldom either necessary or economical to depart from standard thicknesses of lead for purposes of assisting conductivity.

Although perhaps bearing more on Manufacture than on Design, a passing reference to the practice of double-lead covering, which was introduced on the Continent more than twenty-five years ago, may not be out of place, seeing that it is still frequently specified on the Continent and has not entirely disappeared from some British specifications. The practice originated from efforts to overcome difficulties which were encountered in the production of a sound lead sheath, and its application in two thin layers was rather in the nature of a subterfuge, although attempts were made to claim virtues for it.

In this country it was adopted to some extent, though rather more as a matter of fashion or demand than of technical necessity, but as it was economically inferior and from the practical aspect had countervailing disadvantages, such as a tendency for the relatively thin sheaths to corrugate when the cable was bent, the method was soon discarded.

It may be pointed out, however, that if special circumstances demand it there is no reason why a design of cable should not include more than one lead sheath with, for instance, a bitumen sheath interposed between them. Such a combination of sheaths has been used in certain special cases in this country.

Another point which may be mentioned in connection with lead sheaths—

though bearing rather more on usage or maintenance facilities than on the design of the cable—is that external markings in the form of continuous ribs raised on the surface of a lead sheath may be made for purposes of identification of a cable by exterior inspection at any part of its length. A wide range of distinction can be arranged by varying the number of ribs and forming them at different parts of the periphery of the sheath.

This method of distinction, illustrated in Fig. 70, was due to Mr W. J. Howard, Mains Engineer to Sheffield Corporation Electricity Department, and large

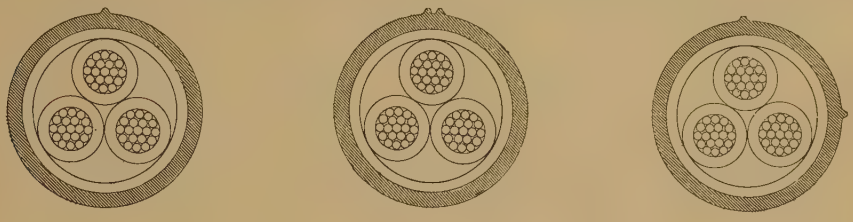

Fig. 70.

quantities of cable have been made with lead sheaths in which this feature has been embodied.

Vulcanised bitumen sheaths were originally simple equivalents of, or non-metallic substitutes for lead sheaths. In 1906,* however, the author introduced the internally ribbed vulcanised bitumen sheath with the object of eliminating fibrous padding material from the interstices between the insulated cores of vulcanised bitumen multicore cables.

Incidentally this construction improved the mechanical properties of this type of cable to a sufficient extent to allow other fibrous material, *i.e.* tapes, etc., on the insulated cores to be eliminated, so that a multicore vulcanised bitumen cable virtually became a solid cylindrical mass of vulcanised bitumen, with its conductors symmetrically embedded in it, though easily separable from the sheath and from each other when required for purposes of end connections, jointing, etc.†

Fig. 71.

Similar sheathing of rubber insulated multicore cable was obviously equally applicable and advantageous, and moreover afforded better protection from moisture and atmospheric influences, etc., than had previously been available. These internally ribbed sheaths are now universally employed for vulcanised bitumen and rubber sheathed cables.

In the case of bitumen-sheathed, paper-insulated multicore cable (paper leadless) it was found mechanically and electrically advantageous to eliminate the overall paper insulation as well as the fibrous paddings, and to apply the ribbed vulcanised bitumen sheath directly over the paper-insulated laid-up cores. This construction, illustrated in Fig. 71, combines the advantages of the paper and vulcanised bitumen

* Patent No. 8238, Beaver and Claremont.

† Glover's "Solbit" cable.

types of cable, the combination being particularly valuable at higher pressures than those to which the vulcanised bitumen type is ordinarily limited, viz., up to about 6000 volts.

In the case of shaped conductor cables this construction affords decided mechanical advantages over the earlier type having part of the paper insulation applied over the laid-up cores, the tendency to uneven relative movement of the cores consequent on bending the cable (see p. 142) being more closely controlled. Electrical superiority naturally follows the mechanical advantage.

Vulcanised bitumen-sheathed varnished cambric insulated cables are made on similar lines to the paper leadless type above mentioned.

Thicknesses of vulcanised bitumen sheath have recently been standardised for both vulcanised bitumen and paper leadless types of cable.

The practice of sheathing vulcanised rubber cables with " tough rubber " or " cab tyre sheath " * has found wide application, though undoubtedly its most effective sphere of utility is in connection with portable or " trailing " work. In effect, a tough rubber sheath may be regarded as a hose in which the conductors of a circuit may be fitted in such a way as to comply with the best mechanical principles of design ; and this, together with the excellent mechanical and generally resistant properties of the special grade of vulcanised rubber sheath itself, enables it to withstand the most onerous combinations of working conditions. The sheath may be reinforced if desired either by embedding woven fabrics, or braids of wire or fibrous materials in it, or by superposing armourings, lappings, or braidings exteriorly upon it.

A form of reinforcement entailing no additional manufacturing operations consists in forming spiral ribs or alternatively studs or " hobnails " of harder rubber on the exterior surface of the sheath in the course of the sheathing operation. This type of reinforcement and the modified type of forcing machine by which it is produced was introduced by the author in 1913.†

Questions relating to the design of various types of armour and protective and preservative coverings, demanded by the widely varying range of practical working conditions, are such that they can be best considered under the headings of " Manufacture " and " Special Conditions," and they are accordingly dealt with in Vol. II.

* Patent No. 3996/11, St Helens Cable and Rubber Co., Ltd.

† Patent No. 13602, Beaver and Claremont.

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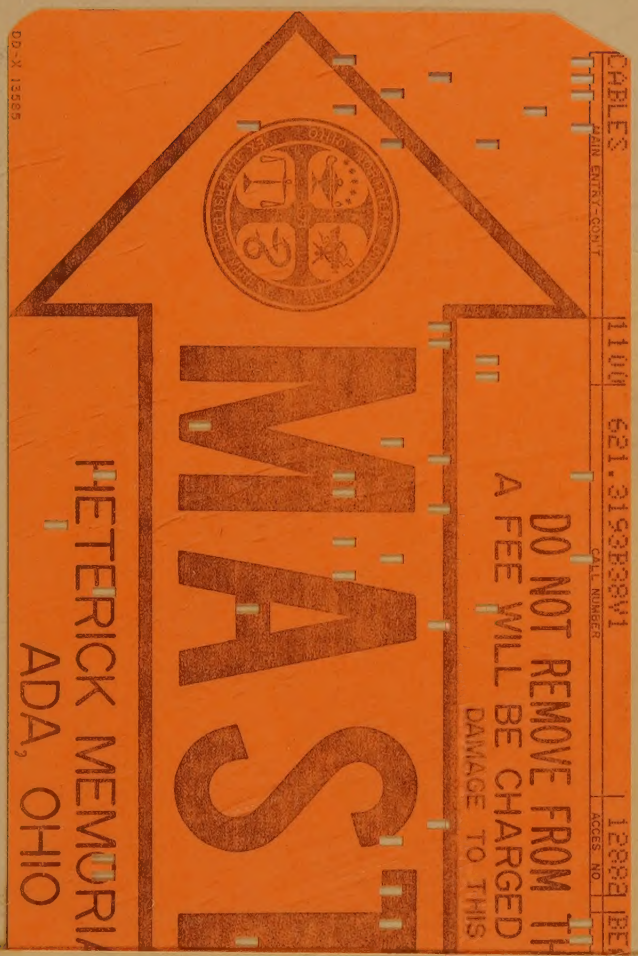

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